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PNSI-TR-69-0301-II

NAVIGATION/TRAFFIC CONTROL STUDY FOR V/STOL AIRCRAFT

(Final Report)

VOLUME II - TECHNICAL

March 1969

Prepared under Contract No: NAS- 12-2024

by
POLHEMUS NAVIGATION SCIENCES, INC.
Burlington, Vermont
(formerly: Ann Arbor, Michigan)

for: Electronics Research Center
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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FOREWORD

Polhemus Navigation Sciences, Inc. was awarded a contract by the National Aeronautics and Space Administration to conduct a study entitled "Navigation/Traffic Control Study for V/STOL Aircraft" (NAS-12-2024). The goal of the study was to provide recommendations to NASA regarding the solution of domestic air traffic control/airborne navigation problems envisioned for 1975-1985. The program was sponsored by the Navigation and Guidance Branch, Electronics Research Center, Cambridge, Massachusetts. Mr. J. R. Coonan served as Technical Monitor for NASA/ERC. Principal investigator for PNSI was Mr. Thomas T. Trexler.

This three-volume final report presents summary results of the NAVTRAC study covering project activity from August 1969 through March 1969. It describes a broad-scope analysis which identifies, from the pilot's viewpoint, the desirable performance characteristics of an advanced navigation/traffic control system for aircraft operating in an environment consisting of V/STOL, CTOL-jet, SST, and general aviation aircraft. A number of recommendations are made for the immediate further research and development of technology related to future airborne avionics systems and air traffic control. The recommended development program has a two-fold design objective: validation of the "Flight Plan Reference/ATC" concept and verification of the effects of automation on pilot workload. Recommendations are made for development of technology associated with NAV SAT and ground-based hyperbolic systems. They include: development of a digital software computer program; man-machine simulation(s) for VTOL and general aviation aircraft; hardware bench and field tests; and qualification flight tests.

The assistance of the following individuals who contributed substantially to the preparation of this document is acknowledged:

Mr. William L. Polhemus	Operations Consultation
Mr. Donald W. Richardson	Engineering Direction
Mr. Linus E. Lensing	Technical Editing and Publication
Mr. Edwin McConkey	Radio Systems Engineering
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Mr. Steven C. Lesak	Pilot Workload Studies

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ABSTRACT

The Navigation Traffic Control Study for V/STOL Aircraft (NAVTRACS) develops recommendations for the further research and development of air traffic control/navigation related technology. The desired performance characteristics of an advanced navigation/air traffic control system for the 1975-1985 domestic air transportation environment are developed from the cockpit viewpoint. V/STOL, CTOL-jet, SST, and general aviation aircraft are considered. The advanced system embodies two new concepts: a Flight Plan Reference System and Limit Logic. The concepts assume the availability of area navigation aids. Five candidate systems are evaluated: NAVSAT, ground based hyperbolic (Decca, Loran C and Omega) and rho theta integrated with course line computer.

Enroute, terminal area and approach and landing requirements are considered. Area navigation, in this context, provides two capabilities: required horizontal position information for the pilot, and ATC system-required surveillance information. To generate the precision required for approach and landing of carrier aircraft, a differential NAVSAT and/or ground based hyperbolic capability must be incorporated into the system if individual runway instrumentation is not to be used.

Acceptability of each area navaid is evaluated through use of comparative pilot workload analysis. For purpose of this study, the pilot workload approach is used to determine desired system level(s) of automation. Detailed Event Sequence Diagrams which cover both VFR and IFR operations define the pilot's tasks of navigation, communication, aircraft control, and system monitoring. . . . . and show the interface between airborne system and ATC. To insure a broadly based workload assessment, several configurations of general aviation and air carrier-type avionics systems are included in the tradeoff analyses.

Volume I of the report contains an overall summary of the results of the study. Volume II (Technical) discusses the technical approach used in the study and describes the results of various tradeoff analyses which lead to the reported conclusions and recommendations. Volume III (Appendices) documents the background technical data generated to support the analyses and system definition.

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LIST OF SYMBOLS AND NOMENCLATURE

o Arabic Letter Listing (lower case)

a	aircraft acceleration
a	radius of the earth
a/c	aircraft
ackn	message acknowledgement
c	speed of light
d	distance from calibration point to user
d	distance from transmitter to user
dm	distance between point of closest approach and transmitter
do	distance between aircraft and point of closest approach
do	calibration point
dP	position error vector
d rms	rms statistic of radial repeatability error
dT	TD error
f	carrier frequency (mHz)
f k Hz	carrier frequency (kHz)
f	frequency
f30, f31	frequency code of third (3) approach path (outer and inner marker beacon)
g	earth gravitational acceleration
g	general aviation aircraft density
g1, . g14	general aviation candidate navigation systems
h	altitude
hni, hn2 . hn3	altitude of the final approach waypoints
ho3, hi3, ho3	command altitude at outer, inner marker beacon and pad, respectively, for the third (3) approach path
n	rms noise field strength
s	horizontal distance in VOR cone of silence
sh	an altitude
s_{at}	an along track distance
s_{ct}	a cross track distance
s	LaPlace operator
t_a	along track separation
t_c	time delay due to propagation over the earth
v1 . v10	aircarrier candidate navigation systems

o Arabic Letter Listing (caps)

A	heading
ABBR	abbreviated report
AC	aircarrier
Ackn	message acknowledgement
ADF	automatic direction finder
AFCS	automatic flight control system
A-G	air-to-ground
AIREP	air report
AILS	advanced instrument landing system
AP	autopilot
ARINC	Aeronautical Radio, Inc.
ARSR	air route surveillance radar
ARU	attitude reference unit
AS	airspeed
ASDE	airfield surveillance detection equipment
ASR	airport surveillance radar
ATA	Air Transport Association
ATC	air traffic control
AT	along track
ATIS	automatic terminal information service
ATT	attitude
ALT	altitude
B	TD receiver constant (rad/sec)
Bw	bandwidth of receiver r.f. section (Hz)
CAS	collision avoidance system
CAS	calibrated airspeed
CAT I, CAT II, CAT III	category or landing conditions
CCC	communication, command and control
C/D	control/display
Comm	communication
CPU	central processing unit
CRT	cathode ray tube
CT	cross track
CTD	cross track distance
CTOL	conventional takeoff and landing
CLC	course line computer
CLR	clearance
CW	continuous wave

o Arabic Letter Listing (caps) - (cont'd)

D	operator transportation lag
D	distance
DA	drift angle
DG	directional gyro
DI	deviation indicator
DIST	distance to go
DOC	direct operating cost
DR	dead reckoning
D rms	rms statistic of radial predictability error
DD rms	rms statistic of radial TD system error
DTD	differential time difference
DTD (GB)	differential time difference - ground based
DTD (NS)	differential time difference - navigation satellite
DTG	distance to go
DME	UHF distance measuring equipment
E	east
E	rms field strength
Eg	rms ground wave field strength
Es	rms sky wave field strength
EET	estimated enroute time
ESD	event sequence diagram
ETA	estimated time of arrival
FAA	Federal Aviation Administration
FL	flight level
FPA	flight path angle
FSS	flight service station
FSK	frequency shift keying
G	transformation matrix
GA	general aviation
G-A	ground-to-air
GA1, GA2, GA3	classes of general aviation aircraft (p 2-11)
GDOP	geometric dilution of precision
GBTD	ground based time difference
GMT	Greenwich Mean Time
GS	landing system glideslope
GS	ground speed
HDG	heading
HF	high frequency
H1, H2, H3	hold waypoints
H(s)	transfer function of receiver tracking loop
HSD	horizontal situation display
HSI	horizontal situation indicator
IAS	indicated airspeed
ID	identification
IFR	instrument
ILS	instrument landing system
IMB	inner marker beacon
IMC	instrument meteorological conditions
IMU	inertial measurement unit
INS	inertial navigation system
IP	intercept point
IRU	inertial reference unit
JFK	John F. Kennedy International Airport
K	operator gain
K	propagation constant
KCAS	knots, calibrated airspeed
KTAS	knots, true airspeed
Lg, Long	aircraft longitude
Lg_D	waypoint or destination longitude
Lg_o	estimate of aircraft longitude
Lt, Lat	aircraft latitude
Lt_D	waypoint or destination latitude
Lt_o	estimate of aircraft latitude
LGA	La Guardia Airport
LF	low frequency
LN1, LN2, LN3.. LWP1	groundpoints or waypoints which define a final approach path
LOC	landing system localizer
LOP	line of position
LOS	line of sight
LWP1, LWP2, LWP3 ..	waypoints which define a final approach path (used with LN1, LN2)

LIST OF SYMBOLS AND NOMENCLATURE (continued)

o Arabic Letter Listing (caps) – (cont'd)

MAA	maximum acceptable altitude
MBR	marker beacon receiver
MEA	minimum enroute altitude
MMD	moving map display
MOCA	minimum obstruction clearance altitude
MRA	minimum reception altitude
M/S	master/slave combination
N	north
N G	navigation and guidance
Nr	number of VOR radials
NAV SAT	navigational satellite
N^2	noise power spectral density
N_p	peak noise voltage
NAVTRACS	Navigation Traffic Control Study
N_A	number of instantaneous users requiring service
NAV	navigation
NOTAMS	notices to airmen
OMB	outer marker beacon
OP	operate mode
P	potential candidate airport for ATC
Pe (s)	phase of the error signal
Pi (s)	phase of the input signal
Po (s)	phase of the output signal
Pr	radiated power (db above one kW)
Pss	steady state phase error
PAR	precision approach radar
PF	position fix
POS	position, latitude, longitude
PPI	pulse position indicator
PT	procedure turn
PVOR/PDME	precision VOR/precision DME
PWI	position warning indicator
Q (s)	position output of inertial platform
R	horizontal distance to a VOR facility
R	general aviation reliever airport
Ro	initial range to waypoint
Rp (d)	spatial autocorrelation function of predictability error
Rr (d)	spatial autocorrelation function of repeatability error
Ro	earth radius
Rpt	report
R/T	receiver/transmitter
RTE	route
RVR	runway visual range
S	south
S	rms signal field strength
Sp	peak signal voltage
SID	standard instrument departure
SID	sudden ionospheric disturbances
SIGMET	significant meteorological conditions
SOP	surface of position
SSR	secondary surveillance radar
SST	supersonic transport
STD	standard
STOL	short takeoff and landing
(T)	airport with ATC tower
T, t	time
Tk	track
To, to	initial time
TAE	track angle error
TAS	true airspeed
TD (GB)	time difference – ground based hyperbolic
TD (NS)	time difference – navigation satellite
TD1, TD2	time difference signal output
TKE	track angle error
TMA	terminal area
T/O	takeoff
TTG	time to go

o Arabic Letter Listing (caps) – (cont'd)

V, v	velocity output of inertial platform
Vat	along track speed
V_g	ground speed
Vct	cross track speed
VFR	visual flight rules
VLF	very low frequency
VMC	visual meteorological condition
V_{MO}	maximum structurally safe operating speed
VOR	very high frequency omnidirectional radio range
VOR (H)	high altitude (jet route) VOR facility
VOR (L)	low altitude VOR facility
VOR (T)	terminal VOR facility
VREF	speed reference for slant track glideslope
WPT	waypoint
WPT1, WPT2, . .	the sequence of waypoints which comprise a flight plan
VWPT	vector waypoint; a waypoint commanded by ATC which differs from the original flight plan waypoint
VWPT1, VWPT2, ...	the sequence of waypoints which comprise a revised flight plan commanded by ATC
Z_A	altitude
ZAC	command altitude

o Greek Letter Listing (lower case)

α	attenuation constant
α	proportionality constant
βm	magnetic course to waypoint
γ	time between pulses
δ	drift angle
δt	time error
ϵa	accelerometer bias error
ϵg	gyro drift rate
$\epsilon \gamma$	deviation of actual from command glideslope on slant track
θ	bearing to a waypoint, facility, or hazard
θ	phase error
λ	wavelength of signal
ρ	slant range to a waypoint, facility, or hazard
ρ	aircarrier and military aircraft density
σ A	3σ heading error
σ AT	3σ along track error
σ CT	3σ cross track error
σ d	standard deviation of position error
σ GS	1σ glideslope error
σ h	3σ altitude error
σ LOC	1σ localizer error
σ P1, σ P2	standard deviation of time error on each path
σ t	standard deviation of time error
σ TD1, σ TD2	standard deviation of time difference error
σ v	3σ speed error
σ	standard deviation of phase error
τA	operator anticipation time constant
τL	operator error smoothing lag time constant
τN	operator short neuromuscular delay
τT	position fixing frequency in terms of track error
τu	position fixing frequency in terms of NAVSAT
φ	relative phase between signal and error voltage
ψ	ionospheric reflection coefficient
ω	radian frequency of carrier signal

o Greek Letter Listing (caps)

Δ	an increment in an associated variable
ΔCT	an increment in crosstrack distance
ΔETA	an increment in ETA
Δf	fractional frequency deviation
Δfuel	an increment in fuel volume
ΔZ, ΔH	an increment in altitude
Δrms	rms statistic of radial DTD system
ΔTD1, TD2.	differential time difference calibration signals
ΔV	an increment in speed

SECTION 1

INTRODUCTION

1.0 GENERAL

Vertical Take Off and Landing (VTOL), Short Take Off and Landing (STOL), Conventional Take Off and Landing (CTOL) jets, SST, and particularly a broad class of general aviation aircraft must be accommodated by the future traffic control system. As one approach to solving the problem, the Navigation Traffic Control Study (NAVTRACS) for VTOL and STOL aircraft examines the use of a number of candidate navigation systems configured to an advanced Air Traffic Control (ATC) system.

ATC is assigned the role of a Communications Command and Control system in which to evaluate future navigation, communication and other onboard aircraft subsystems. Considering the variety of vehicles of varying economic means which present varying subsystem complexity and performance, two general solutions can be proposed:

(1) extensive use of restrictive procedures governing the flow of all air traffic,

or ...

(2) tradeoffs in electronic systems and automation to facilitate the safe, efficient and reliable movement of traffic.

The NAVTRACS study evaluates the use of onboard navigation systems for area navigation and approach and landing. It assesses system capability for supplying independent position and velocity information to the traffic control surveillance unit. The study assesses ATC from the point of view of the pilot, with the premise that ATC has the responsibility to maximize the use of available airspace without compromising safety. The pilot function is to control the aircraft within the ATC constraints. The principal means used in this study to assess the utility of future navigation/traffic control systems is the determination of the extent to which pilot workload is increased or decreased. Pilot workload, therefore, becomes the principal assessment factor which determines necessary areas for automation.

Although a systematic and complete tradeoff of candidate navigation systems requires detailed accuracy, reliability, power, weight, volume, and cost tradeoffs, the NAVTRACS program was restricted to an evaluation of first order accuracy and performance analyses and to a determination of operational requirements. The major tradeoff criteria were pilot viewpoint and pilot workload. The features and functions of an advanced traffic control system were identified, baseline navigation systems with varying degrees of automation were postulated for each user aircraft, and system levels of automation were compared with change in pilot workload.

1.1 SCOPE AND OBJECTIVES

A principal objective of the study was to develop, from the viewpoint of the pilot, an advanced navigation/traffic control system for aircraft operating in a mixed V/STOL, CTOL jet, SST, and general aviation environment forecast for the 1975 to 1985 time frame. NAVTRACS synthesizes a communications, command and control system which is capable of efficiently, expeditiously and safely controlling the forecast domestic traffic, including VTOL, STOL, CTOL jet, SST and general aviation aircraft.

The nature of the pilot's tasks was considered as a major factor in defining requirements of the airborne system in terms of desirable performance characteristics. These characteristics established the guidelines for configuring the communications, command and control system and the area navigation, approach and landing aids. The candidate navigation systems considered were to include at least the following:

- Navigational Satellite (NAV SAT)
- Ground Based Time Difference (GBTD or hyperbolic)
- Radio-inertial

This list was eventually expanded to include Differential Time Difference (DTD) systems and rho-theta (VOR/DME) systems.

Evaluation of the navigation systems as candidates in the advanced navigation/traffic control system required that they provide the following system functions:

(1) supply independent surveillance information to the traffic control system – position and velocity;

(2) provide performance as an area navigation, approach and landing aid; and

(3) provide the pilot with real time information for aircraft control and flight path management.

Alternative navigation systems which met the desired operational capability were configured into advanced navigation traffic control systems of varying levels of automation.

Pilot workload measurements were used to assess the effectiveness of the navigation traffic control system. Pilot/aircraft control and monitor tasks, pilot/ATC communications tasks, and the pilot/avionics system navigation management tasks for VTOL, STOL, SST, CTOL jet and general aviation aircraft were the principal workload areas evaluated. Tradeoffs in pilot workload as a function of navigation/traffic control system-levels of automation led to recommendations regarding technology and future research objectives.

Objectives of the evaluation included:

(1) identification of the desirable performance characteristics of an advanced navigation traffic control system;

(2) configuration and evaluation of candidate navigation traffic control candidate systems in terms of system-levels of automation;

(3) determination of technology recommendations in terms of levels of automation; and

(4) outline of future software simulations, man machine simulations and field experiments to be used to validate conclusions and to verify operational characteristics.

Analyses of pilot workload permitted the development of recommendations for advanced technology support studies, airborne subsystems, ground subsystems, simulations and field tests. Research objectives, determined from the establishment of automation requirements, include programs to develop airborne subsystems, equipments, procedures and software; ground system equipments; software studies; and procedures to accommodate the navigation surveillance information. Software simulations and man-machine simulations are recommended to assess traffic capacity, safety of flight, and flight workloading.

Tests are recommended as programs to validate NAVTRACS conclusions and to verify problem areas associated with the area navigation, approach and landing system when integrated with an advanced traffic command and control system.

1.2 TECHNICAL APPROACH

The block diagram of the technical approach used in this study is shown in Figure 1.

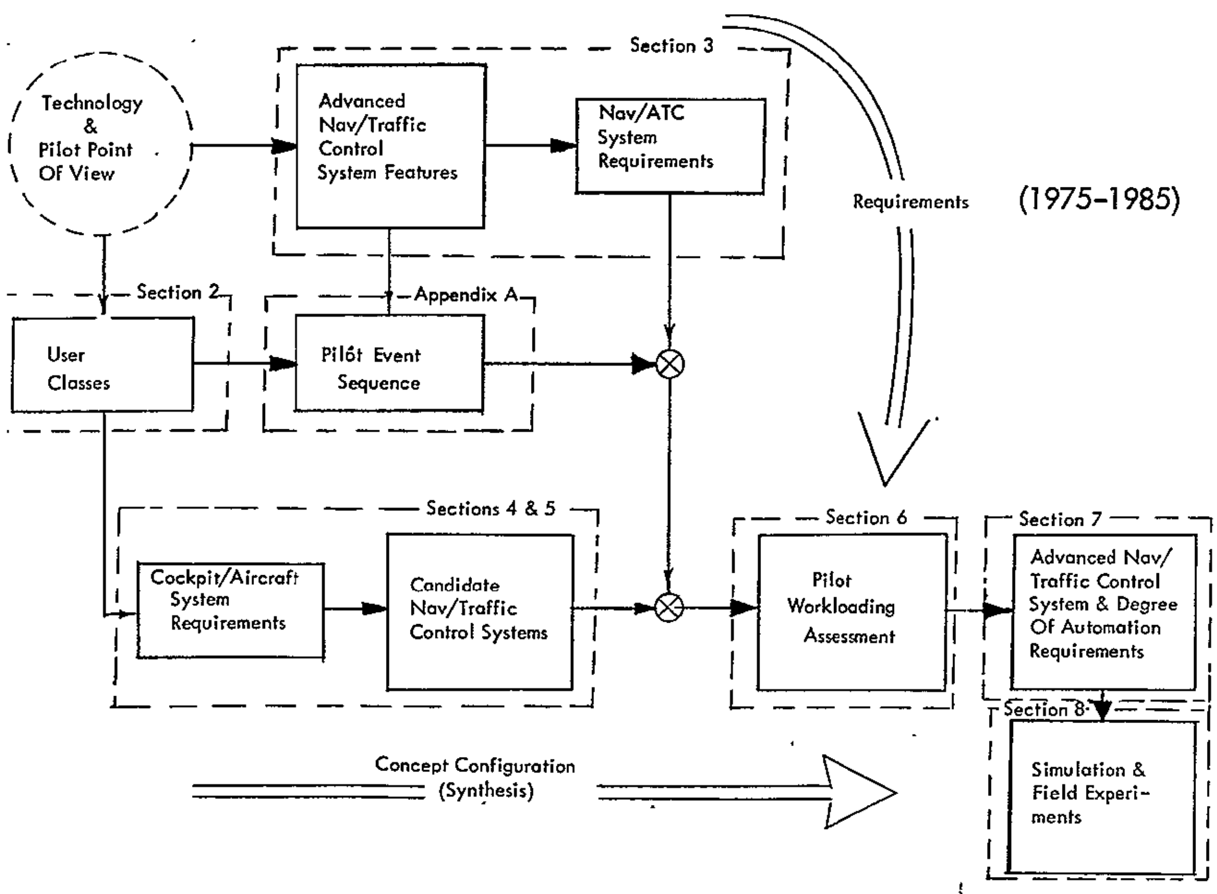


Figure 1. Block Diagram of Study Approach

Technology and Pilot Point of View. Inputs to the program were a review of pertinent technology, and the pilot's point of view. The technology review included current literature contained in the bibliography; current ARINC specifications; and development of the data base of ATC simulations including: position fix, dead reckoning and homing navigation systems, aircraft automatic flight control systems, communication and data display systems, aircraft performance data, and traffic activity forecasts. Pilot point of view, assembled from aircarrier and military aircrews, was used to define navigation functions, pilot information needs and workload times which were utilized as inputs to the pilot workload analyses.

Advanced Navigation Traffic Control Features. Generation of the desirable operational characteristics of the advanced navigation/traffic control was specified from the pilot's viewpoint. The communications, command and control approach was used to develop control, surveillance and advisory functions per flight phase of the user vehicle. These functions were input into the pilot workload analysis and incorporated into the event sequence diagrams for both VFR and IFR controlled airspace flight. In addition, the control, surveillance and advisory functions were configured into a representative ground system which is adaptable to the needs of handling surveillance data linked from the airborne navigation system, in terms of 1975-85 traffic activity forecasts.

Navigation/ATC System Requirements. Communication and navigation system requirements, computed for each user vehicle, are specified in terms of message content and a 3σ accuracy constraint. The communications requirement, in terms of message content and data rate for air-to-ground and ground-to-air messages, was defined for the control and surveillance unit, etc. The 1975 to 1985 traffic density forecast was used to figure the size of the communications requirement for both IFR and VFR flights. The navigation accuracy constraint, derived in part from traffic activity forecasts, separation standards, all weather landing requirements, and ATC time-of-arrival forecast control, specifies 3σ along track/cross track heading and altitude errors, and relates to the ATC control and surveillance unit, the user vehicle, and the flight phase. Although the principal assessment criterion is pilot workload, the navigation and communication requirement established figures of merit for assessing preliminary candidate systems for area navigation, ap-

proach and landing.

User Classes. VTOL, STOL, CTOL jet, SST, and general aviation aircraft type; flight profiles, event times, aircraft subsystem parameters and avionics equipments were specified prior to defining the pilot/aircraft interface, and the aircraft/traffic control system interface. Aircraft performance parameters--including stage lengths, speeds, climb rates, approach paths, approach angles, and ATC speed and altitude constraints--were input to the calculation of aircraft flight profiles. The flight profile times relative to each flight phase established the bounds for pilot workload task times in performing the aircraft control and monitor function, the navigation management function, and the communications management function.

Pilot Event Sequence. Mission-oriented events between pilot, user vehicles, and ATC for each flight phase--including taxi, takeoff, climbout, enroute cruise, descent, approach and land--were constructed in the form of pilot event sequence diagrams. These diagrams, modified to include an advanced traffic command and control system, establish the interface functions between the pilot and aircraft systems, the pilot and the navigation system, and the pilot and the control and surveillance unit. The diagrams portray the operational utilization of an advanced traffic control system. The pilot event sequence diagrams lead to the pilot task analysis and workloading assessment.

Cockpit/Aircraft System Requirements. The candidate navigation system, communication systems, aircraft systems, and control display units were modified to compensate for pilot information needs and the advanced navigation/traffic system requirements.

Candidate NAV/Traffic Control Systems. Candidate area navigation, approach and landing systems, including control/display units, were configured with respect to the avionics complement of the user aircraft. Error analysis for the NAVSAT, GBTD, VOR/DME, and hybrid systems was performed, and candidate systems which did not meet the accuracy constraint of each user system were deleted from consideration in the pilot workloading analysis. Of the remaining systems, those unable to comply with the operational requirement derived in the requirements analysis were also deleted as candidates for the advanced traffic/control system. Various levels of automation of the user system were

configured for further pilot workload evaluation.

Pilot Workloading Assessment. Pilot workload for each user vehicle was used to assess the suitability of candidate navigation systems. Various levels of cockpit and ground system automation were advanced and evaluated in terms of the pilot event sequence diagrams and the proposed ATC concept, i.e. the Flight Plan Reference system. Pilot-synthesized task times (as opposed to man-machine simulation studies) were constructed from discussions with and evaluation of pilot/navigator experience. Visual, manual and voice tasks for all pilot and copilot functions were itemized. Pilot-systhesized task times included consideration of motor functions such as push button data insert, selector function switching, communication times per data word, instrument scan times, and human response times. Workload, as a system automation criterion, sets the task times for aircraft control and monitor functions, navigation management, air-to-ground and ground-to-air communication management.. and is used to measure percent of pilot utilization. Tradeoffs between the percent of pilot utilization and the system-levels of automation were utilized to define the advanced navigation/traffic control system, and the degree of systems automation.

Simulation and Field Experiments. An integrated program defining four areas is outlined: (1) digital software simulation programs to automate the methodology and the Flight Plan Reference event sequence diagram; (2) man-machine simulations to verify traffic safety, traffic capacity, and pilot workload; (3) field experiments to validate navigation system and data link performance; and (4) technology development programs for traffic command and control hardware and software.

1.3 REPORT ORGANIZATION

The NAVTRACS Final Report is organized into three volumes. Volume I presents a summary of the study. Volume II (Technical) describes scope of the study and pertinent results. Volume III (Appendices) contains analytical data supporting the results presented in Volume II and an amplification of the various analyses. Figure 1, a block diagram of the study approach, illustrates the coordination between the sections in Volume II and the study approach.

Section 2 presents a description of the 1975 to 1985 air traffic mission assumed for this study. ATC is organized into a communications, command, and control system. This section also describes the design point criteria selected for seven candidate aircraft typical of the 1975 to 1985 era. The operational requirements were evolved from evaluation of performance parameters, typical short haul and long haul mission profiles, and assumed performance for the selected avionics subsystems. Aircraft performance envelopes and profile geometry of the users are described in this section in the context of specific ATC route structure, flight levels, landing systems and ATC constraints. Surveillance link candidates and surveillance information navigation sources are outlined.

Section 3 summarizes the desired operational capability of ATC, area navigation, and approach and landing systems. Navigation traffic control functions, and navigation and communication system requirements are also presented.

Section 4 discusses the rationale of the advanced navigation traffic control system in terms of system philosophy, form of the airborne system, form of the ground system, and the general area-navigation concept.

Section 5 summarizes the capability of navigation systems to serve as an area navigation, approach, and landing system when configured for the 1975 to 1985 era. VOR/DME, PVOR/PDME, VOR/DME with course line computer, NAVSAT, GBTD (Omega, Loran-C & Decca), Differential NAVSAT, Differential GBTD and hybrid radio-inertial systems are evaluated in terms of the desired operational capability and accuracy requirements of the user vehicles.

Section 6 summarizes the analysis of pilot workload. The Flight Plan Reference, navigation/air traffic control event sequence diagram is reviewed. User hardware and candidate systems, comprising variations in system-levels of automation, are configured. The pilot task analysis, pilot model, and workload methodology are explained. The results of the workload analysis, in terms of execution time and percentage of pilot utilization for each type user aircraft and each candidate system, are presented. These include: (1) the total mission, (2) a single enroute leg, and (3) the terminal area. The potential for reduction of workload through use of increased automation is indicated and quantified.

Section 7 summarizes the fully automated Flight Plan Reference concept, and trades off automation with respect to system type, system accuracy, message execution time, and a system capacity index.

Section 8 presents recommendations for a series of integrated advanced development programs. It also summarizes results and conclusions of the study.

PRIOR TO REVIEWING THIS VOLUME II (TECHNICAL), THE READER IS ENCOURAGED TO EXAMINE THE EVENT SEQUENCE DIAGRAMS CONTAINED IN APPENDIX A OF VOLUME III.

SECTION 2

MISSION REQUIREMENTS

2.0 SUMMARY

This section presents a fundamental description of the 1975 to 1985 air traffic control mission. ATC is organized into a communications, command, and control system and then the users of an advanced, domestic ATC system are defined.

The NAVTRACS study seeks to minimize the cockpit workload induced by an ATC system; hence, the characterization of ATC as a communications, command, and control system is a logical approach--it facilitates analysis at the system level to isolate the cockpit duties to be expected of aircarrier and general aviation pilots.

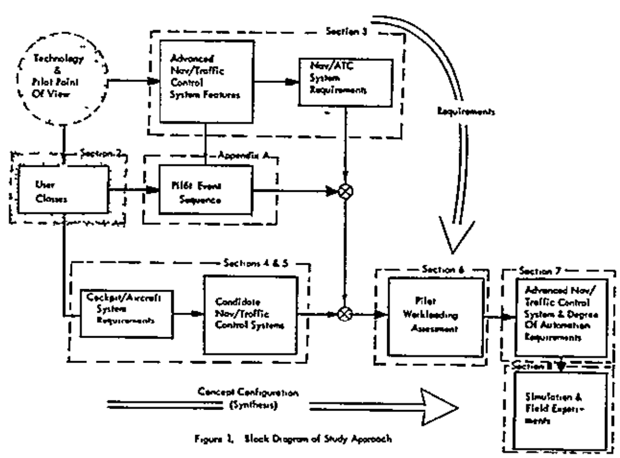


Figure 1. Block Diagram of Study Approach

Following a brief review of the ground based radar surveillance system, an ATC concept is introduced that relies upon surveillance information which is generated from an airborne navigation system. Both position and velocity, derived from an airborne system, can supplement or replace radar surveillance information. The navigation oriented system uses the flight plan as the primary control reference for the airborne and ground systems. The system response, both traffic flow and aircraft flight path management, is measured relative to the flight plan or clearance.

This section defines the general aviation and aircarrier users of the 1975 to 1985 domestic airspace and their mission profiles. VTOL, STOL, CTOL jet, SST and three classes of general aviation aircraft (GA1, GA2, and GA3) are the users. The user performance envelopes, and the flight profile geometry, are described with respect to ATC and the route structures.

The mission profiles of the general aviation and aircarrier vehicles serve several useful purposes. They show the characteristics of the vehicles and varying flight profiles which dictate system capacity and space requirements of the future navigation and traffic control system. They relate the geometry, speed, acceleration and time relationships of each aircraft type to the ATC, area navigation, and approach and landing system. Finally, pilot workload associated with navigation management, communication management, and the aircraft control and monitor tasks is related to mission elapsed time and flight phase. Hence, analysis of the distribution of pilot workload with respect to flight phase and elapsed time can be accomplished.

VTOL and STOL flights are assumed to occur in congested, high density traffic areas between urban area VTOL pads and STOL ports with access limited to feeder, rural, remote CTOL airports. The desired operating altitude for the VTOL and STOL aircraft is seen to be in conflict with CTOL jets. Because their cruise speeds may differ by as much as 50%, ATC is faced with major difficulties in instituting flow control and in maintaining longitudinal separation. This enroute conflict is accompanied by a terminal area conflict. When the VTOL and STOL aircraft penetrate the terminal area airspace, their climb-descent paths are in conflict with general aviation, air taxi aircraft, and with departing and arriving SST and CTOL aircarriers. Any candidate navigation/ATC solution must incorporate the capability for positive control and unambiguous surveillance throughout the flight profile; should permit parallel-track and slant-track operation;speed control and/or path stretching;and volume (3-D AREA NAV) navigation operations.

The advanced navigation system must meet two broad criteria: first, the system must meet the 1975 to 1985 performance requirements for area navigation, approach and landing; and second, it must provide precise airborne-derived surveillance information to replace data derived from ground based radar. Avionics equipments that are currently not fit in user aircraft are: the data link, the small,low cost general purpose computer, and the area navigation system.

Four candidate position-determination systems and a dead-reckoning system are suggested as candidate navaids to meet the area navigation requirement. SST, CTOL, GA3, VTOL, and STOL aircraft are assumed to be equipped with candidate dead-reckoning configurations integrated with one of the position determination system alternatives: NAVSAT, ground based time difference, or rho-theta. These systems apply to terminal area or enroute flight. During the approach and landing phase, the aircarrier and GA3 aircraft might employ the candidate differential NAVSAT, differential ground based time difference, coupled ILS, and/or AILS systems. In contrast to these higher class users, the general aviation aircraft user is restricted to a visual approach and landing.

SECTION 2

MISSION REQUIREMENTS

The performance capabilities and requirements of the ATC system of 1975-85 are tied intimately to the following variables:

- traffic densities expected in the terminal and enroute airspace,
- performance characteristics of the user vehicles, e.g. GA1, 2 and 3, CTOL jet, VTOL, STOL and SST aircraft.
- obligations imposed on the ATC system to guarantee safe separation between aircraft, to advise operators of the proximity of hazards to flight and, where possible, to assure regularity and efficiency of operation
- airspace requirements of the various user vehicles as a function of stage length and passenger facilities (for example, special STOL ports and VTOL pads) and
- the availability, performance and cost of candidate airborne equipment.

The performance requirements of an acceptable future air traffic control system are related to a number of factors which are not intrinsically associated with the problems of separating vehicles, facilitating schedule reliability, or minimizing either indirect or direct operating costs. These factors include consideration of such things as aircraft performance, aircrew complement and proficiency, route structure, passenger service requirements, and availability and cost of airborne hardware.

Obviously, there are a number of different approaches which might be implemented, and each of them offers its own unique advantages. Basically, the problem is to provide the means to process more aircraft, efficiently and safely, than are now being handled by the ATC system. There is, therefore, a temptation to provide

the required increase in system capacity by attaching a multiplier to the existing system, e.g. adding more radars, more flight strips, more communication and more controllers.

Several alternatives to this obviously unacceptable solution have been proposed. Each of these, though apparently capable of providing a major increase to system capacity, would obligate the nation to expend vast new funds, yet fail to satisfy the requirements of all the potential users of the air transportation system.

The major requirement in the 1975-1985 ATC system is to accommodate a vastly increased number of aircraft with widely dissimilar performance characteristics, flown by pilots of significantly different experience and proficiency.

It is anticipated that general aviation will continue to grow at an exciting pace and it is expected that this area will, in fact, create the major technological challenge to the system designer. This challenge is due, in part, to the limited dollars available to the GA pilot with which to equip his aircraft for operation in a densely populated airspace. Furthermore, the ratio of single-pilot to two-pilot operations will probably remain high, about as it is today (again for economic reasons). However, the single pilot's ability to cope with the multiplicity of new cockpit demands, and his proficiency, will probably not look much better than they do now.

Since it is certainly not in the national interest to inhibit the growth of general aviation, the only acceptable alternative is to find a way to create the means for the GA pilot to interface with the ATC system with the same degree of competence, precision and reliability as does the professional pilot team of a commercial carrier.

The present set of procedures, regulations and aids which governs and facilitates air navigation and air traffic control should be altered so as to close the present open-loop VFR Flight Plan form of operation, substituting the higher standard of nearly automatic in-cockpit navigation. This would reduce aircraft-ground communications, yet keep the cost to the airborne user at a reasonable level.

A solution <u>which includes the GA user</u> will be a solution <u>for all users</u> of the airspace.

In summary, then, the general requirements on the desirable system are these: (1) to provide for continuous information, at the cognizant ATC center, of current aircraft position and intentions (this applies to all users of airspace); (2) to provide maximum flexibility of operation regardless of performance characteristics of the various users; and (3) to reduce all unnecessary workload in the cockpit to an absolute minimum so that even the marginally proficient pilot can cope with the demands of the system.

2.1 SYSTEM ORGANIZATION

The structure of the present ATC system is reviewed in the following paragraphs and the relationships between ATC and aircraft are discussed in terms of surveillance, control and advisory services.

2.1.1 <u>Radar Surveillance ATC</u>

The aircraft surveillance requirement is presently performed through utilization of a combination of flight data strips, pilot reports and ground based radar. IFR flights are required to maintain track, altitude and speed within specified bounds set by an approved flight plan or clearance, or vectors supplied by the controller through voice commands. VFR flights, on the other hand, are presently free from any such constraints. It is the responsibility of the VFR pilot to operate his aircraft so as to avoid the possibility of collision. ATC has primary responsibility for maintaining safe separation of IFR traffic units, including the provision of advisory information concerning the proximity of other vehicles to an aircraft operating on an IFR clearance.

The position of the IFR aircraft is monitored by the ATC surveillance radar. The pilot checks his progress (ETA, fuel state) against the flight plan, comparing measured position with his assigned routes. The checks are usually performed when above a

VORTAC station, at intersections of VOR radials, or by using pilotage check points. When under radar vectoring,either in the enroute airspace or in the terminal area, responsibility for aircraft navigation is assumed by the controller. In controlled airspace, the ATC ground system maintains surveillance of the airborne system. An aircraft operating under continuous radar surveillance is said to be under positive control. The ground based radar measures aircraft slant range and true bearing with respect to the antenna. Altitude and identification information is supplied to the ground facility by the aircraft from a coded airborne transponder in response to an interrogation which is keyed in synchronization with the primary skin tracking radar. The raw data is then processed and displayed on the ATC display, and, when required, is also output on Flight Data Strips.

Aircraft progress is monitored by the Air Route Traffic Control Center (ARTCC) or the Terminal Area Control area surveillance team. Should the surveillance team detect a potential conflict--hazard situation, deviation from assigned flight plan, or deviation from assigned radar vector--it will impose a constraint on the flow of IFR traffic to relieve the situation. The necessary command data is linked to the aircraft by voice. Thereafter the pilot receiving the instruction is required to modify the flight path of his aircraft in accordance with the required change. This command loop does not exist for VFR traffic, although a pilot on a VFR clearance can ask for assistance if he wishes.

The ARTCC maintains surveillance and control of all high and low altitude enroute traffic operating on an IFR clearance, certain holding areas and IFR traffic operating between terminal areas.

The ARTCC area is usually subdivided into sectors in order to distribute workload in a systematic way. These sectors are responsible for their respective high and low altitude enroute traffic, for certain holding areas, and for coordinating traffic flow between terminal areas.

Within any Center there will be an unspecified number of terminals which come under the cognizance of a unit called Approach Control. This unit is responsible for terminal area traffic, usually below 14,500 feet. The Approach Control unit within a Terminal Area or Hub is generally configured to handle several air terminals.

Two more levels of assistance at the local level are available to the pilot. The first is called Tower Control and the second, Ground Control. Tower Control is responsible for control of departing aircraft from just prior to entry to the runway to completion of take-off, and for arriving aircraft from beginning of final approach to landing. Ground Control is responsible for control of departing aircraft from the parking ramp to the runup position, and for arriving aircraft from completion of landing until the aircraft has reached its parking position.

Table 1 summarizes the ATC services which are available to the pilot.

2.1.2 Communications, Command and Control

The air traffic control system provides three general functions - surveillance, control and advisory service. Figure 2 illustrates the organization of the current air traffic control system.

The carriers generally operate their aircraft on an IFR clearance which is filed with ATC by the airline's dispatcher. The majority of general aviation aircraft operate on VFR flight plans and thus are not within the control loop. During the 1975 to 1985 time frame, GA aircraft operations will outnumber air carrier operations by ratios of from 10:1 to 18:1. Upon request of the GA pilot, a flight plan covering a cross country flight will be accepted by ATC through a Flight Service Station. This information is retained in an open file until the flight is completed and the pilot requests that it be closed. In the event that he forgets to perform this task after landing, Air Rescue facilities are alerted to begin search.

A fundamental relationship is maintained between the pilot and the control and surveillance unit. The flow of traffic is regulated at the discretion of the controller, subject to pilot acceptance of instructions. Control is implemented through compliance with IFR and VFR procedures. The surveillance function requires knowledge of aircraft present position and intentions.

The pilot interacts with the ATC through his effort to make good his flight

TABLE I
AIR TRAFFIC SERVICES

SERVICE	AREA	USERS	INFORMATION
Flight Service Station	Outside Controlled Airspace (within 5 mi. of airport without control tower)	IFR Flights, VFR Flights	(1) Collision Hazards (2) Altimeter Setting (3) Preflight Briefing Wx, Enroute Navaid, Term (4) Can Authorize Clearance (5) Monitor VFR Flights over water, mountains, etc. for S & R (6) Flight Plans (7) Collision Avoidance Vector
Air Route Traffic Control Service (ARTCC)	Controlled Airspace (principally enroute)	IFR Flights	(1) Altimeter Setting Service (2) Jet Route Advisory Service (3) Collision Hazards of other Traffic (4) Provides information to see and avoid other traffic
Approach Control, Departure Control	Terminal Area	IFR Flights, sometimes VFR	(1) Control (2) Surveillance (3) Traffic Flow Information (4) Wind, Runway, Traffic
Automatic Terminal Information Service		IFR Flights in high density control areas	Essential, repetitive information

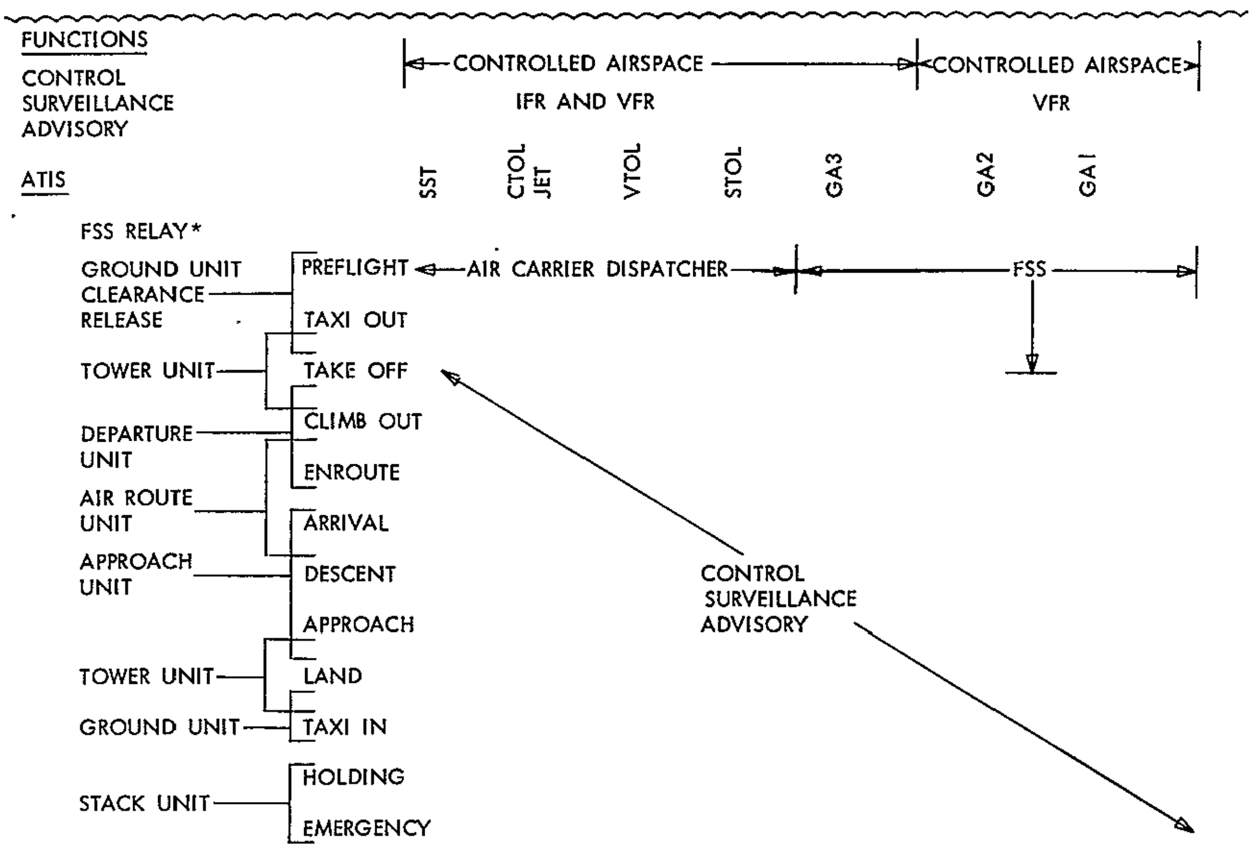


Figure 2. Air Traffic Control System - Organization

plan, by complying with ATC steering commands, by using specified frequencies for communication, by properly setting transponder code, and by complying with approved clearances and/or clearance amendments. Surveillance data is provided from radar and pilot position reports. Advisories supplied to the aircraft include information about other traffic, weather, hazards to flight, and Air Terminal Information Service (ATIS) data such as wind direction and velocity, runway conditions, altimeter settings, etc.

Figure 3 illustrates the interface between airborne user and ATC system. The diagram also introduces the element of pilot workload related to navigation management, communications, and aircraft control and monitor tasks. The control reference is assumed to be the aircraft flight plan, which is a primary input to both the airborne and ground based systems. The flight plan used as a reference in the proposed system is the principal control tool of the system. It provides the means to alert both pilot and air traffic controller to any deviations from expected system behavior.

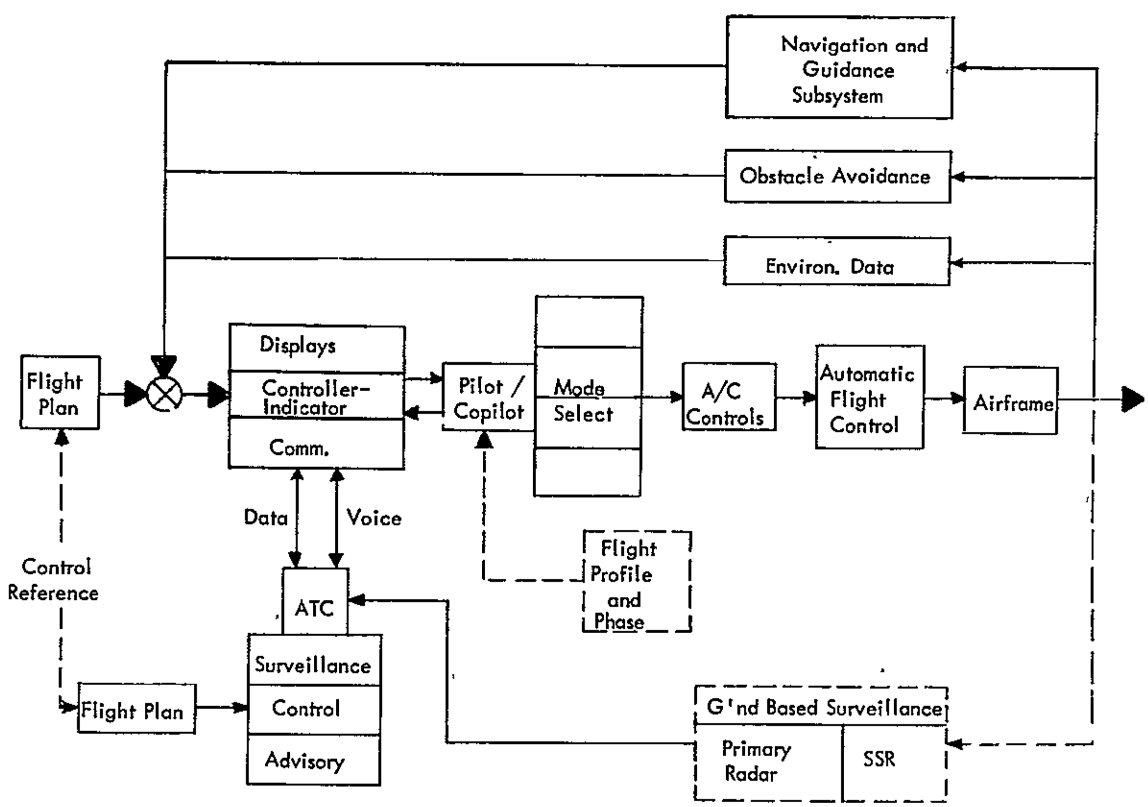


Figure 3. Generalized Airborne and CCC System, Functional Flow Diagram

Aircraft position is input to the ground based system from radar surveillance data which is supplemented with other navigational data supplied by the pilot. Performance of the radar surveillance system (in terms of accuracy of measurement and availability of service) varies as a function of number of vehicles under surveillance, weather, equipment and controller workload.

An independent source of surveillance information can be generated from the airborne navigation system.

It is visualized that the future ATC system would first be upgraded by complementing the ground based radar information through use of position deviation from flight plan.

The use of an area navigation system capability can greatly assist the pilot in all phases of flight. Position and velocity data derived by the airborne system could be used to supplement or to replace data derived by the ground system.

A minimal upgrading of the present ATC system could retain and utilize most of the organizational structure of the existing system but would probably require the consolidation of computational centers. Consideration of the the precise structure of the ground based elements of the ATC system is beyond the scope of this study. Suffice it to say that it was assumed that the ATC functions of control, surveillance and advisory service would continue to be the major identifiable features of the future ATC structure.

The principal communication roles are summarized below:

Air-To-Ground, (A-G), Surveillance. The Pilot Report, Standard Report or AIREP includes aircraft identification, position, altitude, time, next waypoint or destination, and Estimated Time of Arrival (ETA).

Ground-To-Air, (G-A), Command, or A-G Request. The principal G-A commands are initiated by the controller for the purpose of supplying or amending a clearance, for hazard avoidance, for modifying the flow of traffic to preclude a potential conflict between aircraft, or to provide a block of airspace for an aircraft seeking to

enter the system. As the aircraft leaves one sector or terminal area and enters another, it will be directed to change the voice communication frequency it is using and to modify its transponder code portion of the Command setting. ATC requests for aircraft identification and message acknowledgement also comprise a large portion of the Command communications load.

Advisory (A-G and G-A) Service. The advisory function includes the transmission of altimeter settings, traffic advisories or meteorological data. The continually transmitted, repetitive ATIS Messages which include information about wind direction and speed, altimeter setting, runways in operation, NOTAMS, known traffic, airport traffic patterns, and special instrument approach procedures concerning a particular terminal, are provided either by ATC in response to a specific request of a pilot or on the ATIS channel (Air Terminal Information Service).

2.2 USERS OF THE SYSTEM

The users of the proposed advanced navigation traffic control system, NAVTRACS, will be general aviation, the commercial carriers and military aircraft. Typical aircraft forecast to be operational during the 1975 to 1985 time frame were used as design point vehicles in order to develop representative flight profiles, to develop an appreciation of significant differences in performance characteristics, e.g. cruise speed, rate of climb, minimum approach speed, etc.; to develop information about the geometry of the aircraft flight profiles with respect to terminal area and enroute traffic control, the navigation systems, and approach and landing systems. This information permitted the construction of event sequence diagrams for use in computation of pilot workload.

2.2.1 Kinds of Aircraft

Table II summarizes the aircraft selected for evaluation in this study. The Mach 2.0 cruise speed Concorde was selected as the candidate SST, and the Mach 0.8 cruise speed DC-8 as the representative CTOL jet. Both of these aircraft were configured for the typical transcontinental or trans ocean non-stop flight, termed "long haul". Two

TABLE II
USERS OF THE ADVANCED NAVIGATION/TRAFFIC CONTROL SYSTEM

FACTOR	VTOL			STOL		GA			CTOL Jet	SST
	Turbo prop Tilt wing	Lift Fan	Heli-copter	Turbo Jet	Turbo prop	GA 1*	GA 2**	GA 3		
Aircraft Type or Forerunner	XC-142	XV-5A	H-47	CTOL Jet	Breguet 941	Cessna 150 & 172	Beech Bonanza & Piper Navajo	Jet Star	DC-8	Concorde
Range (nm)	435	435	200	435	435	380	800	1800	4500	3400
Cruise Speed) (KTAS)	355 (425)***	435 (485)	155	435 (450)	340 (340)	95	210	445	480	1175 (M=2)
Cruise Altitude (1000 ft)	30 (5)***	30 (5)	10	30 (10)	25 (5)	6	9	35	35	57
Climb Speed (KTAS)	260	400		208		70	120	270	270-490	525-1030
Climb Rate (fpm)	1000-4000	1000-4700	1700	1000-2500		500	1000	2000-3500	3000	1000-7000
Descent Rate (fpm)	1000-3000	1000-3800	1000	1000-3000		500	500-1000	500-6000	2000	1000-10,000
Descent Speed (KTAS)	450	410		435		70	85	125	315-256	1100-345
VMC Approach Slope (deg)	3-12	3-12		3-11	3-11	7	7	3	3	3

* Equipped for VFR only
** Equipped for IFR, but predominately VFR operational
*** Parentheses indicate 174 nmi stage length

types of VTOL aircraft (Ref. 6, 7, 8 and 15) were considered; a turbo-prop tilt-wing aircraft and a turbofan vehicle were declared candidates for the 200 to 500 nmi short haul air carrier mission. The mission of less than 200 nmi was classed as an air-taxi operation in which the helicopter was used as the candidate vehicle. The STOL aircraft, which complements the VTOL aircraft on the 200 to 500 nmi short haul missions, was selected from the turbofan and turbo prop candidate aircraft. The general aviation aircraft were subdivided into three categories, GA1, GA2 and GA3. This subdivision was used to differentiate between the professional pilot who typically flys a corporate jet aircraft GA3, and the non-professional, and sometimes marginally proficient, pilot who flies small reciprocating-engined aircraft. Within this latter set, two further divisions were made: GA1 was used to describe the small aircraft equipped with minimal avionics gear; GA2 is typified by the $45,000 price range, well-equipped, single engine retractable,

or small twin-engined, privately-owned aircraft. Note: military aircraft were not considered in this study beyond accounting for their impact on traffic forecasts.

2.2.1.1 Pilots and Avionics Fit

Generally, the aircraft were considered to possess avionics equipment which is distinctly separable into two levels of performance, primarily as a function of cost. Pilot performance was also assumed to be divisible into two categories, professional and non-professional. The latter category implies fewer flying hours per year, less training, and greater vulnerability to workload increases from factors external to the aircraft.

2.2.1.2 Aircraft Operations

It is well known that the number of general aviation flights significantly outnumbers aircarrier operations. The activity ratio forecast for 1980 for busy hour operations in a major hub is 15 to 1. Since GA1 and GA2 flights are now, and are forecast to remain, predominantly VFR (10 VFR flights to 1 IFR flight), the system is faced with the prospect of a largely open-loop operation in which control over the system is limited.

2.2.2 VTOL and STOL Aircraft

References 6, 7 and 13 identify air carrier VTOL and STOL aircraft configurations postulated for use on the short route segments of the Northeast, California, and Gulf Coast Corridors.

The aircraft used as the candidate vehicles in this study are tabulated in Table III. No reason was found to modify the view expressed in professional circles that service over relatively short stage lengths can be made sufficiently attractive to enough prospective passengers in the 1975-85 time frame to become an economically viable element in the total air transport system. Typical loading was assumed to be 90 passengers.

2.2.2.1 Pilot Workload Candidates

The V/STOL aircraft vehicles selected for further study were:

(1) Turbo prop, tilt wing VTOL typified by the XC-142
(2) Lift fan VTOL typified by the XV-5A
(3) Turbo fan STOL, typified by the Breguet 941/McDonnell 188E

While the aircraft listed above are largely engineering forerunners, they are significant to this study in that the control techniques and functions, and the pilot functions,provide notice of expected pilot tasks, thus forming the basis for an examination of a workload baseline for use with these aircraft. For example, the forerunner of the tilt wing VTOL, the XC-142, will utilize a tail rotor to control pitch. While the air carrier versions would probably use monocyclic control or jet engine control, recorded experience with the present configurations permits one to identify a task which may compete for the pilot's attention during a moment when a navigation or communication task is called for. Although pilot workload during take-off, hover, and conversion would appear to exceed that of a CTOL or STOL aircraft, the pilot functions in climb-out, cruise and descent are expected to be similar to those typical of conventional aircraft.

2.2.2.2 VTOL and STOL Cruise Performance

Stage Lengths. VTOL and STOL aircraft are designed to operate profitably over short stage lengths. Typical are the 100, 300, up to 500 nmi stage lengths between city pairs in the California Corridor, and the 405 nmi stage between Boston and Washington. These potentially short stage lengths imply a dependence on a good vertical navigation capability and high communications workload.

Cruise Conditions. The cruise,true air speed/altitude performance envelope is shown in Figure 4. The potential range of cruise speeds over the design altitude regime of the 100-500 mile stage lengths is seen to be 380 kts to 515 kts. This is a variation in speed of nearly 30% and may present significant flow control and longitudinal separation problems to ATC. The altitude envelope ranges from 25,000 to 35,000 feet. Should

TABLE III
1970-1980 VTOL AND STOL AIRCRAFT *(Recommended Designs)

LTV	BOEING	McDONNELL**	Forerunner
2000 ft. Turbo-prop STOL	-	Deflected Slipstream STOL	Breguet 941/ McDonnell 188E
-	Turbo fan STOL	-	All Turbo fan Jets
Tilt Wing VTOL	Tilt Wing VTOL	Tilt Wing VTOL	XC-142
Fan In Wing V/STOL	Lift Fan VTOL	Lift Cruise Fan VTOL	XV-5A

* 60, 90, and 120 passenger configuration

** CTOL Jet, a modified DC-9, forms part of service system

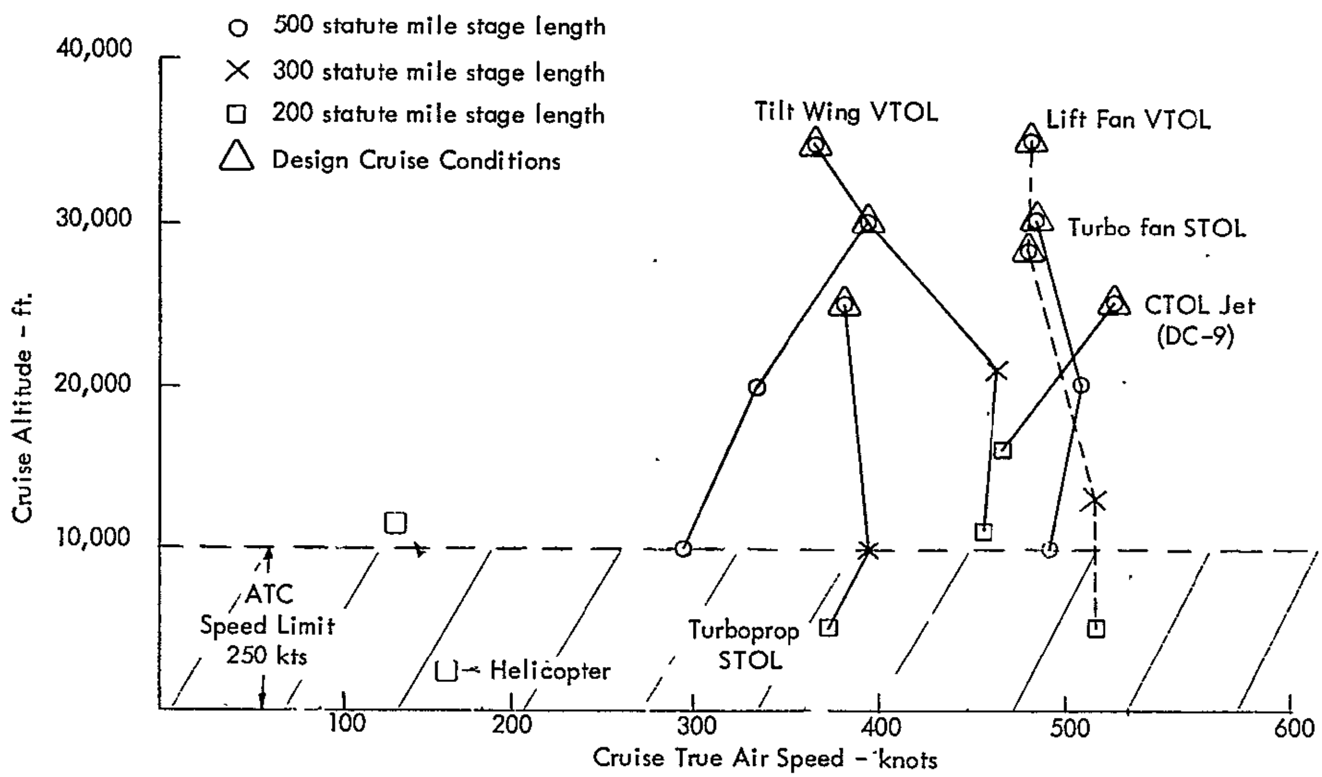


Figure 4 Cruise Performance Envelope VTOL and STOL Aircraft

present rules regarding flight levels available to IFR traffic remain in effect during the period of interest, only four tracks would be available for vehicles proceeding in the same direction. The possibility of wide differences in cruise speed and the limited number of tracks create the need for a system of parallel and slant tracks. Another factor of significance regarding these new aircraft is that the cruise altitudes of the feasible VTOL and STOL aircraft coincide with the altitudes used by the CTOL jet which cruises at 480 kts. Thus these aircraft will be competing for the same airspace.

ATC Coverage. Because of the large numbers of vehicles forecast to be operational in the period of interest, it is apparent that all available airspace will be put to use to accommodate them. Selection of altitude and cruise speed will probably be made as a function of altitude, direction of flight, and proximity to landing area. Thus the ability to accept speed control and to operate economically well away from the optimum altitude will become a necessity. The ATC service area for STOL and VTOL thus becomes defined as a region between 1500 feet and approximately 35,000 feet over a distance of 500 miles. Aircraft true airspeed in cruise will range between 174 kts for the helicopter to 510 kts for V/STOL. What is more significant is that these aircraft can at present accept only a small variation in speed at any altitude.

2.2.3 User Aircraft Cruise Condition

A summary of the user aircraft cruise conditions is illustrated in Figure 5.

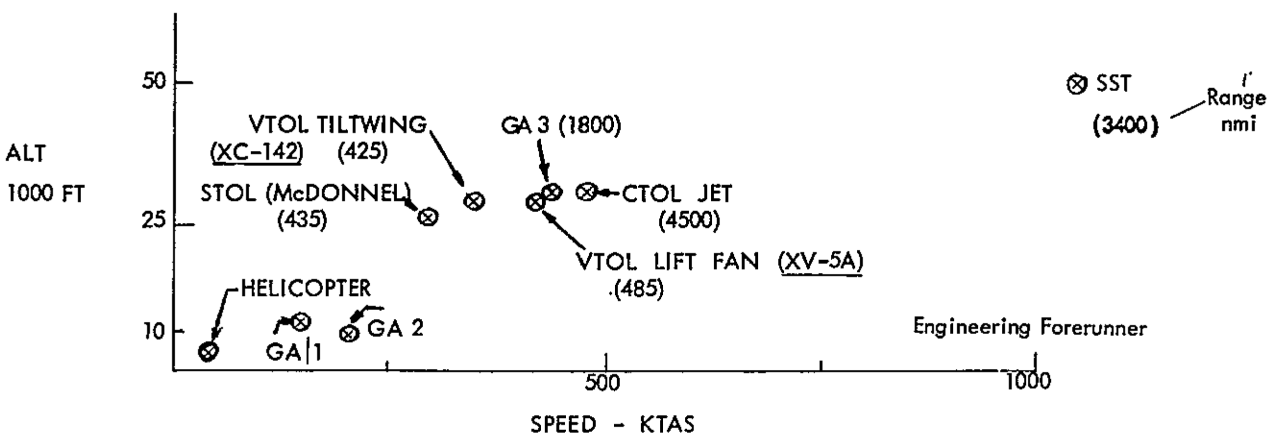


Figure 5. User Aircraft Cruise Conditions

Information is presented on cruise altitudes, cruise speeds and mission range. The cruise regime of the SST isolates that vehicle, while enroute, from the remaining traffic. General aviation aircraft and air taxi helicopters will tend to remain in the lower altitudes below 12,000 feet, while the subsonic vehicles of the air carriers will cluster in the altitude regime from 25,000 to 35,000 ft.

Although the dispersion of cruise altitudes will afford a measure of separation, the potential variation ot user-aircraft operating true-airspeeds suggests the possibility of a significant speed control problem. The region between 25,000 and 35,000 ft will contain aircraft whose cruise speeds differ by nearly 50%. This same range is found at the lower flight levels in the region occupied by general aviation aircraft GA1 and GA2, and the air taxi. The need to maintain schedule, to operate as close to the aircraft's design cruise speed, and the necessity to guarantee safe separation between aircraft imposes contradictory requirements and increases the difficulty of the situation. The use of parallel and slant tracks and speed control could provide a partial solution.

Stage length is also a factor in the separation of aircraft. It is expected that both short haul and long haul aircraft, typified by V/STOL and CTOL jet, will utilize the region between 25,000 and 35,000 ft. Deviations from the direct track dictated by the ATC in order to effect flow control or to separate aircraft produces a relatively smaller increase in DOC for the long haul user than it does for the GA aircraft or carrier operating over a short stage length because extra distance traveled will be a smaller percentage of the total distance traveled. This will of course impact on DOC, and perhaps fuel reserves. Again, the use of a parallel and slant track system provides a partial solution.

The major traffic component, GA1 and GA2 aircraft, is contained in the altitude regime between 6,000 and 12,000 ft; however, the climb and descent portion of the flight associated with departure and approach mixes the entire set of aircraft. The higher performance aircraft, in climbing to and descending from cruise altitude, obviously must penetrate the cruise flight regime of the general aviation and air taxi aircraft. As a consequence, traffic congestion problems will increase significantly in the 1975 to 1985

time frame. The ratio of general aviation to air carrier and GA3 busy-hour operations is forecast to be 15:1.

2.2.4 User Missions and Flight Profiles

Flight profiles for each type of user aircraft were constructed to permit correlation of those elements of the air transport system which were of significance to this study: ATC, aircraft performance, mission events, navigation tasks, approach procedures, communication links, pilot, operating envelope and time. These data are used for several functions:

(1) to relate aircraft profile geometry, system capacity, and space requirements to enroute and terminal area traffic control (discussed in Section 3)

(2) to relate geometry, speeds, and accelerations to the area navigation and approach and landing system (discussed in Section 4)

(3) to constrain the pilot/ATC Event Sequence Diagrams (described in Appendix A)

(4) to define the relationships between requirements, events time, thereby to permit analysis of the distribution of pilot communication, navigation and aircraft control and monitor workload (discussed in Section 6)

The flight profiles of the air carrier and general aviation aircraft are subdivided into the flight phases: taxi, take-off, climb out, cruise, descent, approach and land. These flight phases are considered in the context of IFR direct flight (simulating area navigation) with the following operational constraints:

(1) Minimum Obstruction Clearance Altitude (MOCA) over metropolitan areas had to be greater than 1000 ft.

(2) Air Transport Association requirement that the time spent at cruise power should be equivalent to at least one-half the total airborne time

(3) A conventional instrument approach was assumed

(4) Rules regarding passenger comfort were:

Acceleration should be	$\leq$ 0.5g (landing)
Acceleration should be	$\leq$ 0.25g (inflight)
Cabin angle - climb out	$\leq$ 15° (VTOL, STOL)
Cabin angle - climb out	$\leq$ 12° (CTOL jet)
Cabin angle - descent	$\geq$ -6°
Bank angle	$\leq$ 30°

The acceleration parameters were defined in order to establish the performance criteria on the dynamic tracking of a Ground Based Time Difference area navigation system.

(5) Altitude vs. speed limits had to be observed in order to avoid either high or low speed stall

(6) Speed approach constraints:

Maximum of 200 kts CAS in the airport/terminal area for turbine-powered aircraft

156 kts CAS in the airport/terminal area for piston-powered aircraft

The SST was permitted to utilize an expedited departure and climb out

(7) Standard rate turns of 3 degrees/sec were assumed

Such constraints as noise abatement procedures and optimal flight profiles (climb at speed for best rate of climb, minimum time, or minimum fuel climb profiles) were not considered.

The timing per event is listed in associated tables, together with average true air speed, altitude, climb rates, descent rates and flight path angles. It was determined during the analysis performed in this study that variations in the basic flight profiles cause only minor variations in the times for the event sequence structure and pilot work analysis.

2.2.4.1 VTOL and STOL Flight Profiles

The VTOL and STOL flight profiles derived in this study are shown in Figures 6, 7, 8 and 9. Take-off and climb-out is shown in Figure 6; Figure 7 illustrates conversion and climb to cruise altitude; and Figure 9 shows the approach and landing phase. The boundaries of the terminal area, inferring high density traffic, are shown. The enroute flight phase is omitted, and the descent phase, shown in Figure 8, illustrates the penetration to the terminal area.

Detailed mission times and significant flight parameters are tabulated in Tables IV and V for 500 nmi missions. The identification letters on Figures 6, 7, 8 and 9 establish event times.

(1) Table IV - Tilt Wing VTOL — 500 nmi stage length

(2) Table V - Turbo prop STOL — 500 nmi stage length

Figure 7 and Figure 8 show the VTOL and STOL aircraft flight profiles within a nominal terminal area envelope. Penetration of the terminal area occurs at an altitude of 10,000 ft. From that point, approximately eleven minutes is required (Table V) to complete the flight. The eleven minutes of operation at terminal area altitudes places the vehicle in conflict with general aviation aircraft and air taxi vehicles which are cruising in this flight regime. In addition, the traffic must be directed to unique STOL ports or VTOL pads in the terminal area, thus cutting across the established paths into the larger airports which service the CTOL aircraft. Control and surveillance must be maintained in a region of diverse aircraft types.

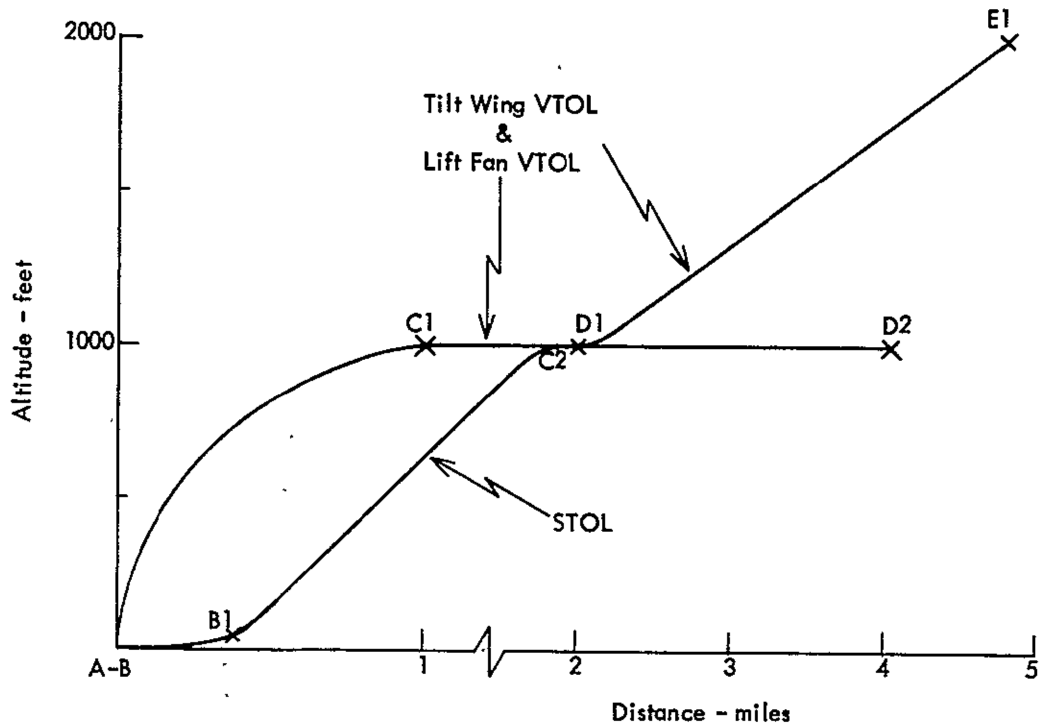


Figure 6. Taxi, Climb-Out - Nominal Mission Profile VTOL and STOL Aircraft

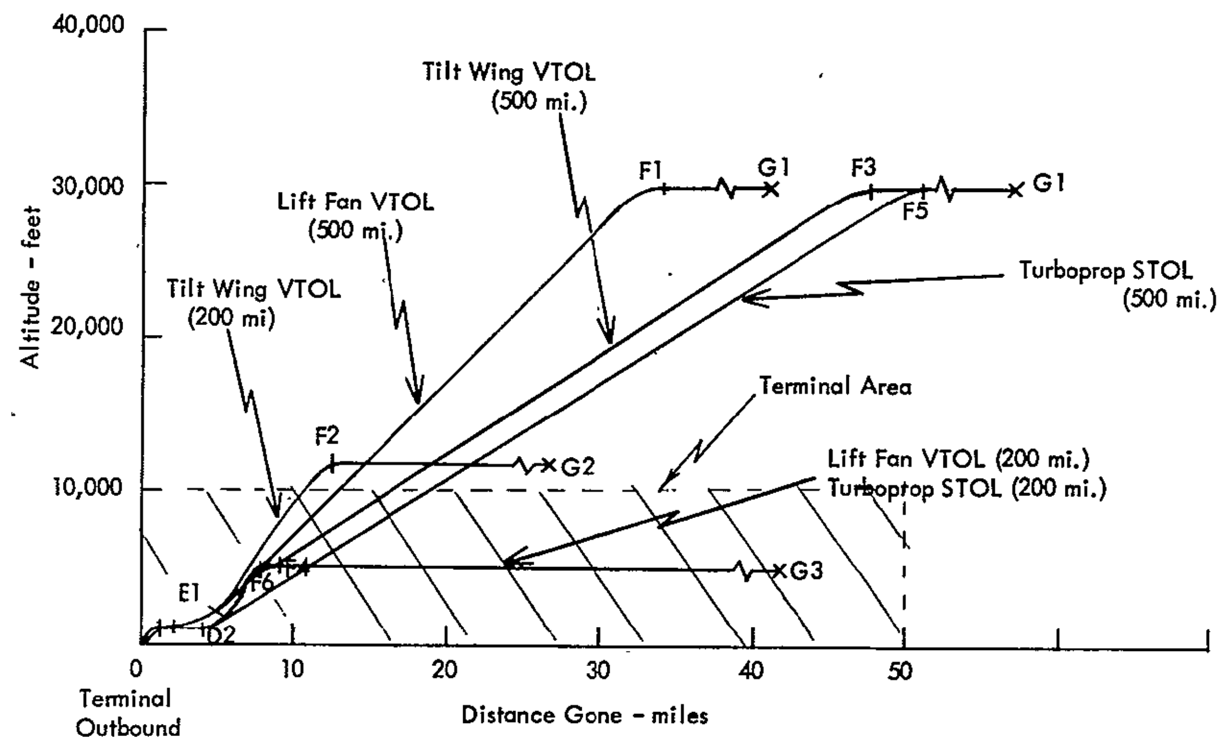


Figure 7. Climb-Out, Cruise - Nominal Mission Profile - VTOL and STOL Aircraft

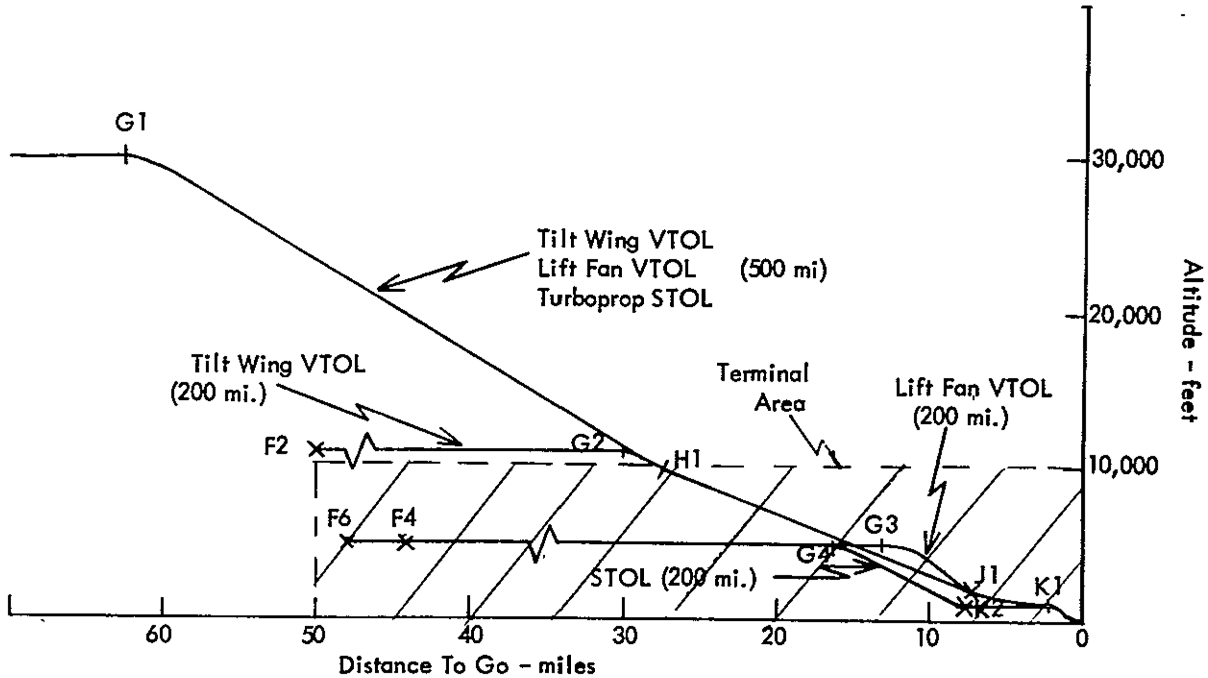


Figure 8. Enroute, Descent - Nominal Mission Profile - VTOL and STOL Aircraft

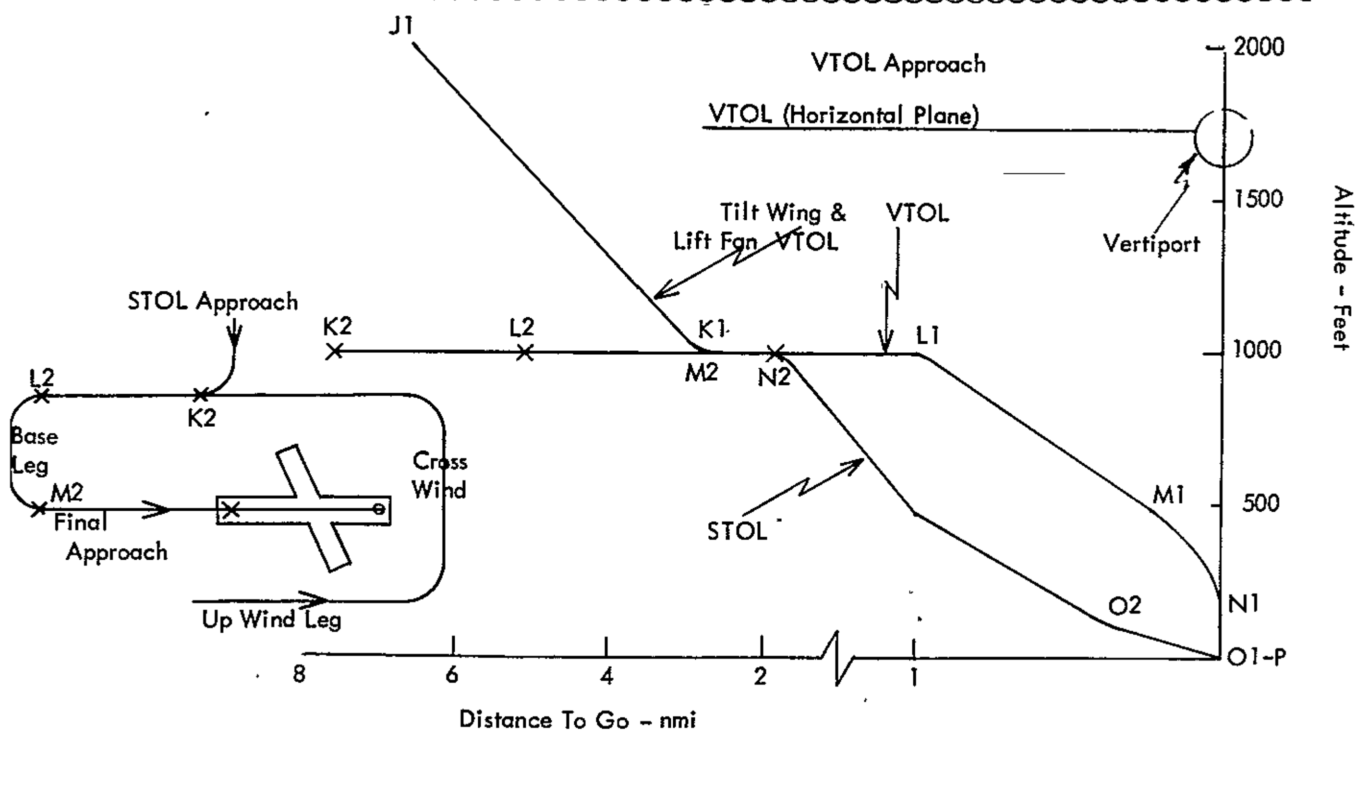


Figure 9. Final Approach and Landing - Nominal Mission Profile - VTOL and STOL Aircraft

TABLE IV
NOMINAL MISSION PROFILE VTOL TILT-WING AIRCRAFT (500-mile Stage Length)

Flight Profile Phase	Segment	Function	Time min.	Time per Event min.	*Average TAS (kts)	Average Vertical Rate, fpm	Flight Path Angle, deg.	Total Dist. Travelled miles	Altitude, ft. (Avg.)
Taxi Out	A-B		0.0	1.5	8			350 ft.	
Take Off[1]	B-C1	Clear to 1000 ft. MOCA	1.5	2.5	172(C1)	1000	90-0.0	1.0	1,000
Climb Out[2]	C1-D1	Accelerate for climb	2.5	0.2	200 230(D)	0.0		2.0	1,000
	D1-E1	Conversion	2.7	1.0	230	1000	3	4.8	2,000
Climb Out	E1-F1		3.7	10.7	300	4000	7	34	30,000
Enroute Cruise	F1-G1		657	55.0	440	0.0	0.0	438	30,000
Descent	G1-H1		61.6	6.6	440	3000	-7	473	10,000
	H1-J1	ATC	68.2	5.3	290	1500	-3	493	2,000
	J1-K1	Conversion	73.5	3.8	230 172(K1)	1000	-3	497	1,000
Final Approach	K1-L1	Align to ILS Localizer	77.3	0.8	161 150(L1)	0	0	499	1,000
	L1-M1	Align to Glide Slope	78.1	0.3	140 130(M1)	1200	-11	499	500
Land	M1-N1	Kill TAS	78.4	0.3	0(N1)	500	90°	500	200
	N1-O1		78.7	0.5	0	400	90°	500	0
Taxi In	O1-P		79.2	1.5	8			350 ft.	

1 vertical acceleration 0.1g, horizontal 0.15g

2 horizontal acceleration 0.25g

* Parenthesis indicates TAS at segment point.

TABLE V
NOMINAL MISSION PROFILE, STOL AIRCRAFT (500-mile Stage Length)

Flight Profile Phase	Segment	Function	Time min.	Time per Event min.	Average TAS (kts)	Average Vertical Rate, fpm	Flight Path Angle deg.	Total Dist Travelled miles	(Avg.) Altitude, ft.
Taxi Out	A-B		0.0	3.0	10			2500 ft.	
Take Off	B-C2	Clear to 1000 ft MOCA	3.0	0.3	92(B1) 138(C2)	3000	7	1.9	1,000
Climb Out	C2-D2	Accelerate to Climb Speed	3.3	0.8	180 223(C2)	0.0	0.0	4.0	1,000
	D2-F5	Attain Cruise Alt.	4.1	11.5	240	2500	6	51	30,000
Enroute Cruise	F5-G1		15.6	51.6	450	0.0	0.0	438	30,000
Descent	G1-H1		67.2	6.6	450	3000	-7	472	10,000
	H1-J1		73.8	5.3	290	1500	-3	497	2,000
	J1-K2		79.1	3.8	230 172(K1)	1000	-3	499	1,000
Approach	K2-L2	Down wind Leg	82.9	1.0	155 138(L2)	0.0	0.0	501.5	1,000
	L2-M2		83.9	1.0	120 103(M2)	0.0	0.0	503.5	1,000
Final Approach	M2-N2	Align Localizer	84.9	0.6	103	0.0	0.0	505.5	1,000
	N2-O2	Align GS	85.5	1.3	75	720	-6	507	100
Land	O2-O1		86.8	0.3	75	0.0	-3	507.2	0.0
Taxi In	O1-P		87.1	3.0	10	-			

2.2.4.2 General Aviation, CTOL and SST Flight Profiles

Figure 10 shows the horizontal profile for GA1 and GA2 aircraft operating

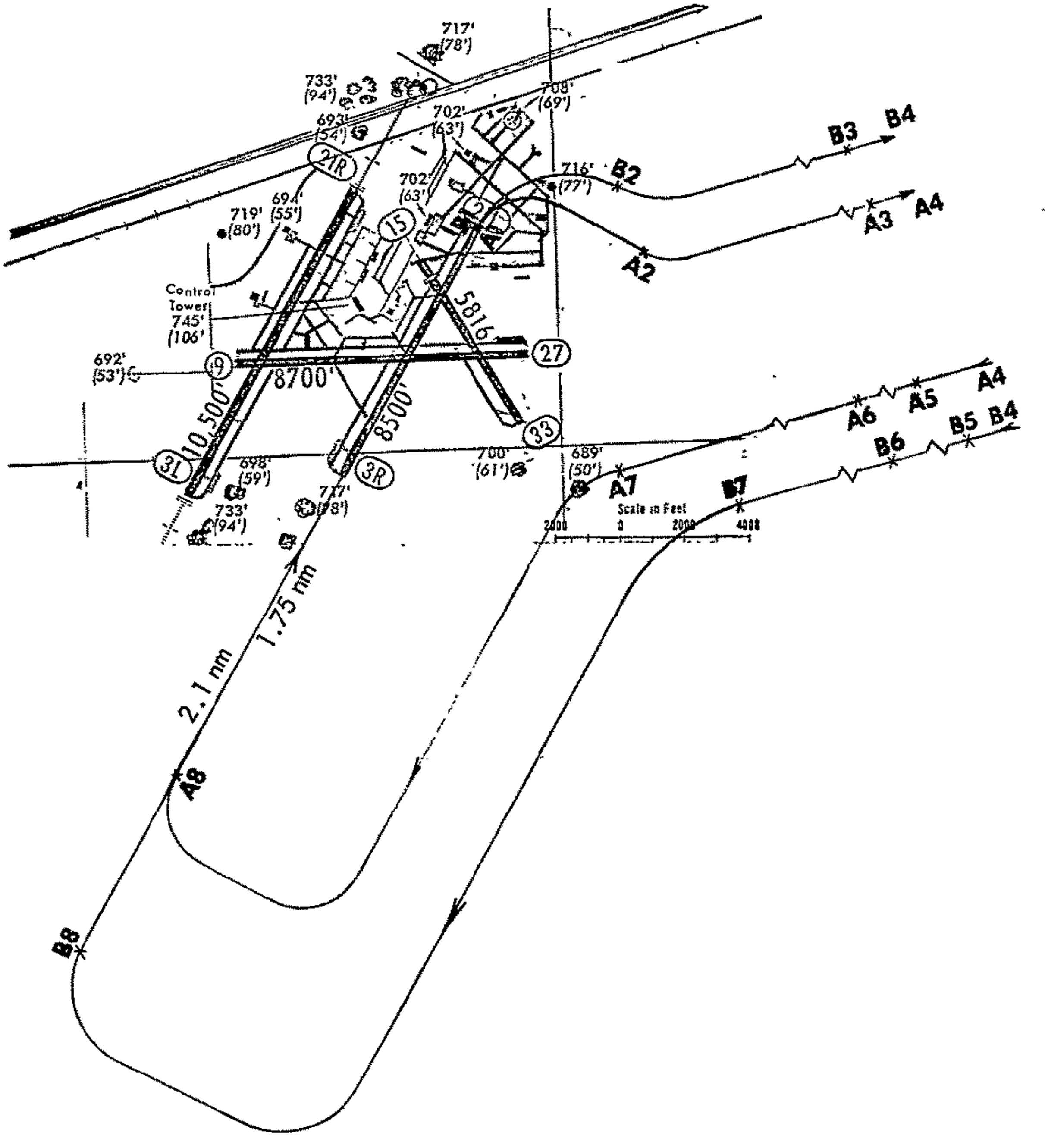


Figure 10. GA-1 and GA-2 Aircraft, 'Nominal Horizontal Mission Profiles ('VFR')

in the region defined as the terminal area. Similarly, Figure 11 shows the horizontal profile for GA3 and CTOL aircraft. The departure and climb-out and descent and arrival profiles for GA1, GA2, GA3 and CTOL aircraft are shown in Figure 12. The SST terminal area profile is displayed in Figure 13. Figure 14 illustrates SST direct take-off and climb out. Also shown in Figure 14 is the final approach and land phases of flight. The ascent and descent phases of the profile are displayed in Figures 15 and 16 respectively.

The "letter designators" (A1, B1 . . . . .) printed on the trajectories appearing in Figures 10 through 15 can be related to the tabular description of the profile contained in Tables VI through X.

The horizontal profiles were constructed with the assumption that an area navigation capability was available. For instance, in Figure 11, "letter designators" C2, D2, D6, C6 and the designators for holding points represent defined waypoints.

The GA1 and GA2 aircraft profiles were constructed in the context of VFR rules and procedures. Thus the take-off, departure, approach and landing were accomplished under control of a tower operator at a controlled airport. Profiles for GA3, CTOL and SST aircraft were constructed in the context of IFR rules and procedures. Control of take-off and landing for these three aircraft was assumed to be under direction of an FAA-operator Tower; departure and approach was assumed to be under control of the Approach Control unit of ATC; clearance and enroute control was assumed to be under the direction of ARTCC, which in fact acts as the coordinating agency for the entire operation. For purposes of exercising the system, all IFR operations were assumed to require the pilot to control and navigate his aircraft by reference to instruments and avionics equipment.

The model profiles for these aircraft were structured around the Detroit Terminal Area (TMA). The SST profile was structured around operations in the Boston TMA. Minor variations in these profiles could be expected for operations within other terminal areas. However, the impact upon the workload measurements should be minimal.

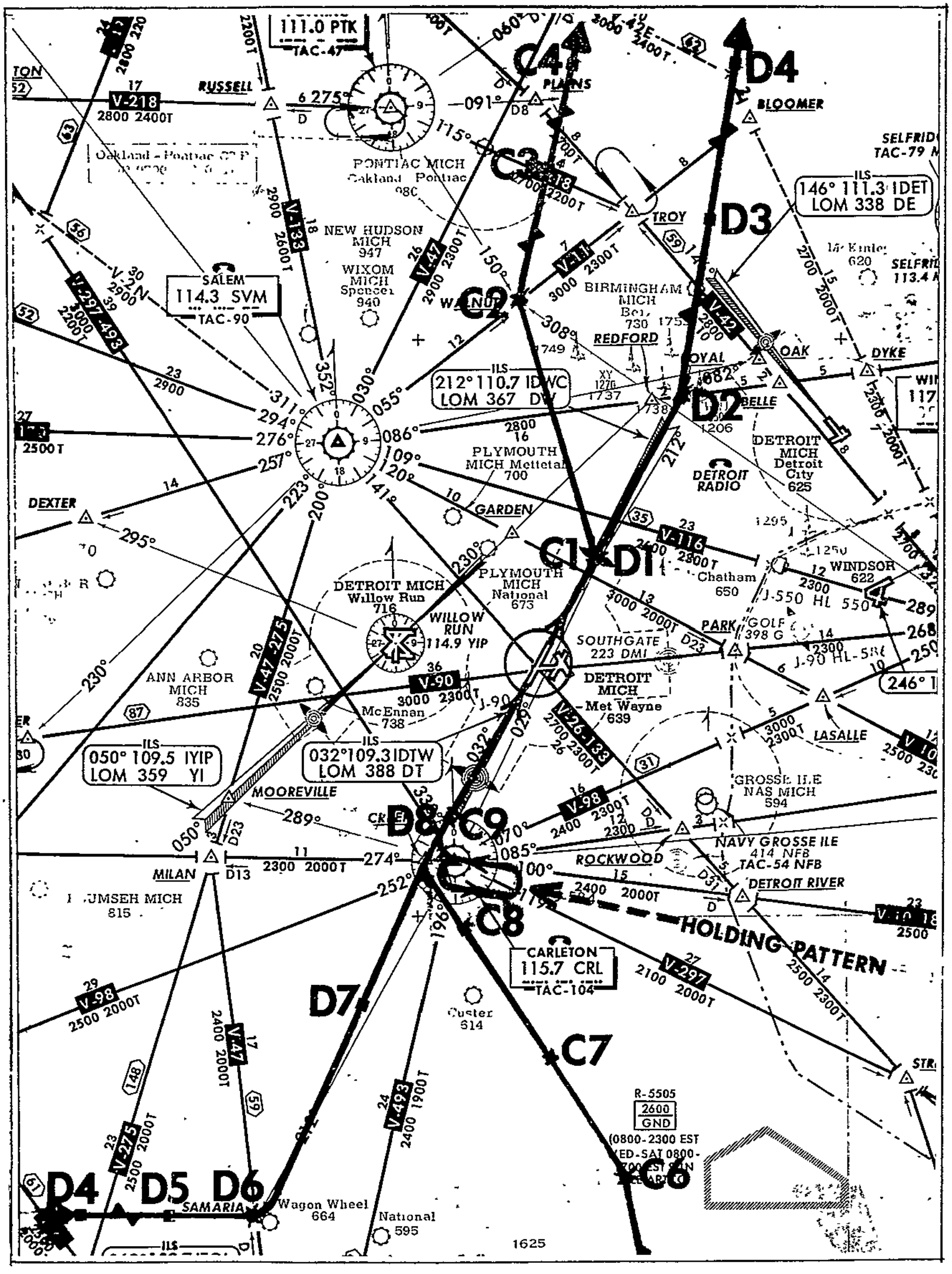


Figure 11. GA3 and CTOL Aircraft, Nominal Horizontal Mission Profiles

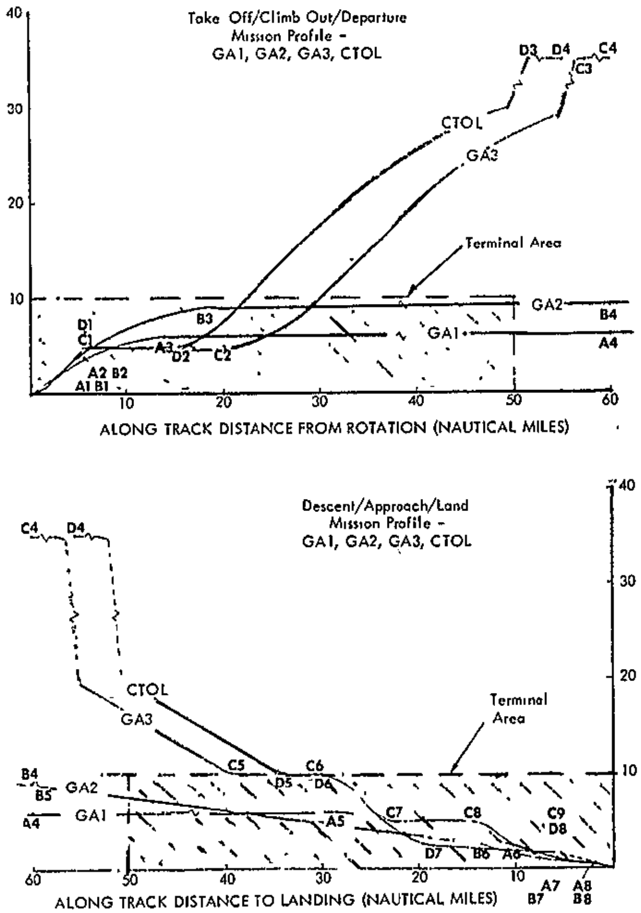


Figure 12. GA1, GA2, GA3 and CTOL Aircraft, Nominal Vertical Mission Profiles

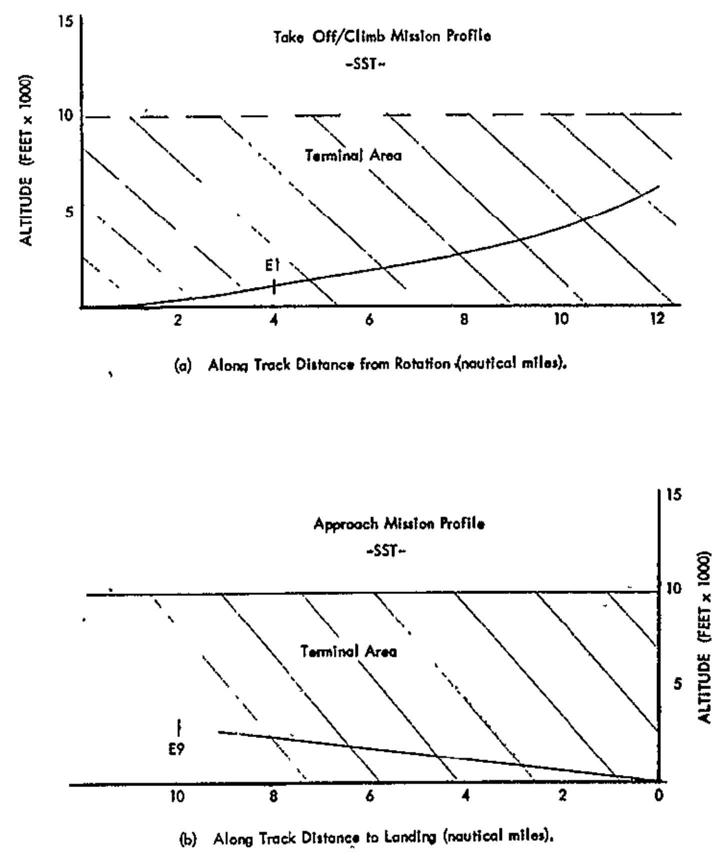


Figure 13. SST Aircraft, Nominal Vertical Mission Profiles, Take-off/Climb, and Approach and Landing

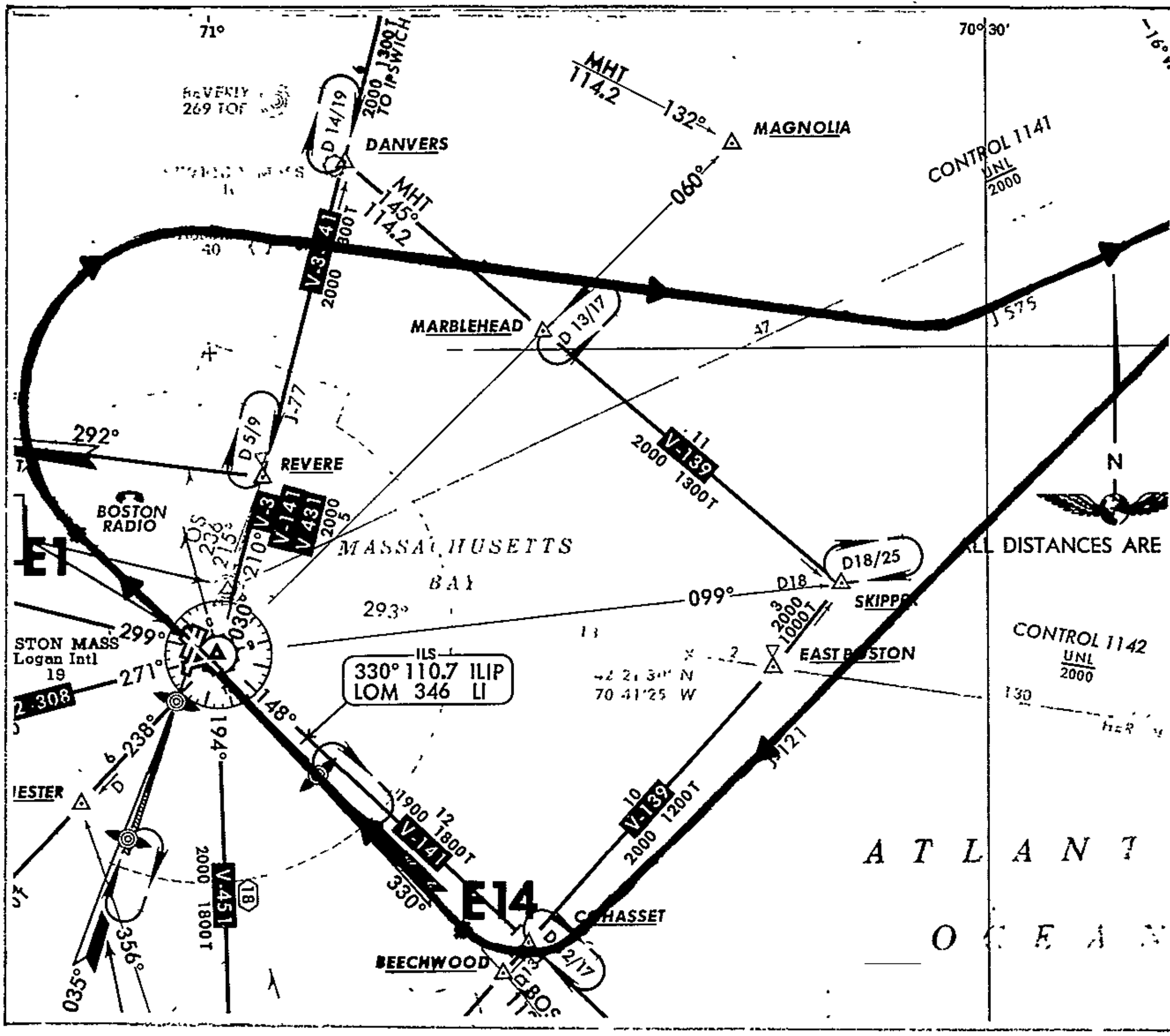


Figure 14. SST Aircraft, Nominal Horizontal Mission Profile

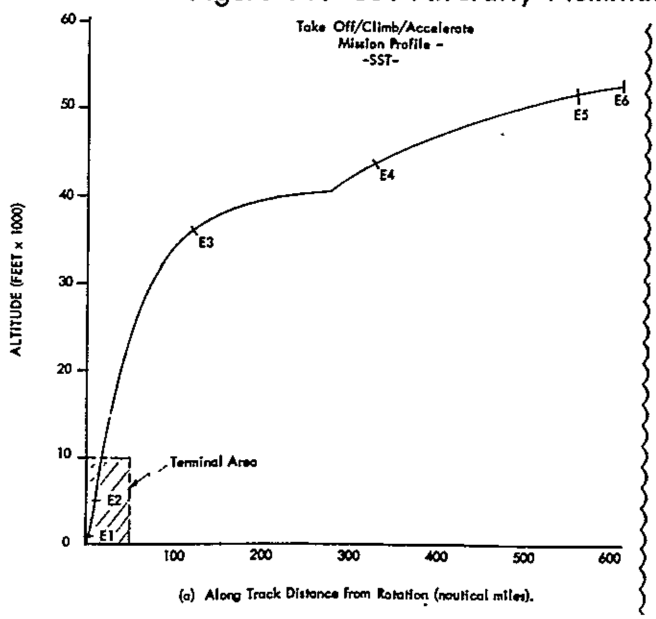


Figure 15. Climb-Out

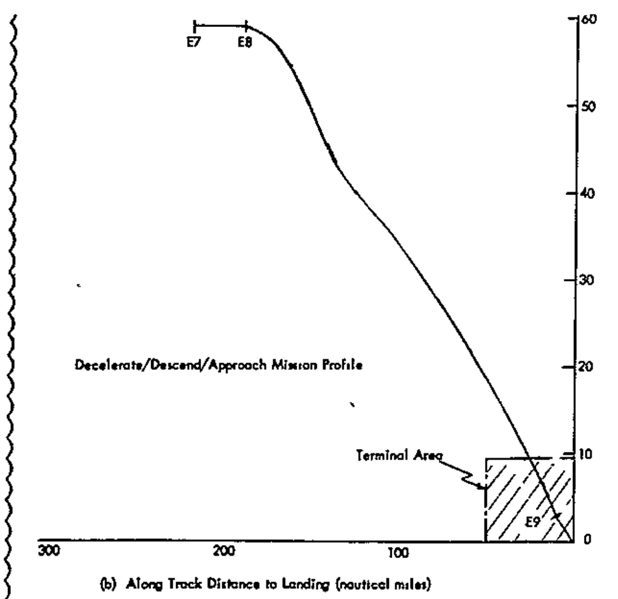


Figure 16. Descent

SST Aircraft, Nominal Vertical Mission Profile

TABLE VI
GA1 AIRCRAFT FLIGHT PROFILE

Flight Profile Phase	Segment	Function	Time min.	Time per Event min.	Average TAS (kts)	Average Vertical Rate, fpm	Flt Path Angle deg.	Total Dist. Travelled nm*	Altitude ft. (Average)
Take Off	0-A1		0.0	1	70	500	4	1.2	500
Climb	A1-A2		1.0	0.7	70	714	6	2.0	1000
Climb	A2-A3	Depart Pattern	1.7	10.3	70	485	4	14.0	6000
Climb	A3-A4-A5		12.0	148.5	95	0	0	-28.8	6000
Descent	A5-A6		160.5	11.7	95	500	-2	-10.3	2500
Descent	A6-A7	Enter Pattern	172.2	3.0	95	462	-3	- 5.8	1000
Approach	A7-A8		175.2	3.3	70	333	-1	- 1.8	500
	A8-Land		178.5	1.5					0

TABLE VII
GA2 AIRCRAFT FLIGHT PROFILE

Flight Profile Phase	Segment	Function	Time min.	Time per Event min.	Average TAS (kts)	Average Vertical Rate, fpm	Flight Path Angle deg.	Total Dist. Travelled nm*	Altitude ft. (Average)
Take Off	0-B1		0.0	0.5	120	1000	4	1.2	500
Climb	B1-B2		0.5	0.5	120	1000	6	2.0	1000
Climb	B2-B3	Depart Pattern	1.0	8.0	120	1000	5	18.0	9000
Cruise	B3-B4-B5		9.0	150.7	210	0	0	-59.0	9000
Descend	B5-B6		159.7	13.0	210	500	-1	-13.5	2500
Descend	B6-B7	Enter Pattern	172.7	3.0	120	500	-2	-7.5	1000
Approach	B7-B8		175.7	2.6	120	333	-1	-2.1	500
Final	B8-Land		178.5	1.5					0

* Positive value indicates distance gone, while minus sign denotes distance to go to touchdown.

TABLE VIII
GA3 AIRCRAFT FLIGHT PROFILE

Flight Profile Phase	Segment	Function	Time min.	Time per Event min.	Average TAS (kts)	Average Vertical Rate, fpm	Flight Path Angle deg.	Total Dist. Travelled nm*	Altitude ft. (Average)
Take Off	0-C1		0.0	1.5	250	3333	8	6.3	5000
Level	C1-C2	ATC Handoff	1.5	3.3	250	0	0	20.0	5000
Climb	C2-C3		4.8	12.0	250 at alt. ≤ 10k ft 270 at alt. > 10k ft	2500	5	74.0	35000
Cruise	C3-C4		16.8	146.2	445	0	0	-60.2	35000
Descend	C4-C5		163.0	5.5	445	4500	-6	-39.0	10000
Level	C5-C6		168.5	2.0	250	0	0	-30.8	10000
Descend	C6-C7		170.5	2.0	250	2500	-6	-22.5	5000
Level	C7-C8	ATC Handoff	172.5	2.0	250	0	0	-14.3	5000
Descend	C8-C9	Acquire ILS & GS	174.5	1.5	250	835	-5	-8.0	1661
Final	C9-Land		176.0	4.0			-3		0

TABLE IX
CTOL AIRCRAFT FLIGHT PROFILE

Flight Profile Phase	Segment	Function	Time min.	Time per Event min.	Average TAS (kts)	Average Vertical Rate, fpm	Flight Path Angle deg.	Total Dist Travelled nm*	Altitude ft. (Average)
Take Off	0-D1		0.0	1.5	250	3333	8	6.3	5000
Level	D1-D2		1.5	2.3	250	0	0	15.7	5000
Climb	D2-		3.8	1.7	250	3012	7	22.5	10000
Climb	-D3		5.5	8.3	400	3000	4	78.0	35000
Cruise	D3-D4		13.8	91.9	480	0	0	-74.3	35000
Descend	D4-D5		105.7	5.0	480	5000	-6	-34.3	10000
Level	D5-D6		110.7	1.0	250	0	0	-30.1	10000
Descend	D6-D7	ATC Handoff	111.7	3.0	250	2500	-6	-18.6	2500
Descend	D7-D8	Acquire ILS & GS	114.7	2.5	250	300	-1.	-8.0	1661
Final	D8-Land		117.2	2.8			-3		0

* Positive value indicates distance gone, while minus sign denotes distance to go to touchdown.

TABLE X
SST AIRCRAFT FLIGHT PROFILE

Flight Profile Phase	Segment	Function	Start CAS (kts)	End CAS (kts)	Start GS (kts)	End GS (kts)	Avg. GS (kts)	Total Dist. (nmi)	Climb Rate (fpm)	Avg. Climb Rate (fpm)	Flight Path Angle (deg)	End Altitude (ft)	Time per Event (min)	Time (min)	Dist. (nmi)
Take Off & Accel.	0-E1	Rotation to 1000 ft	200	240	200	240	220	4	0	1000	≈6.3	1000	1.0	1.0	4
Climb-1	E1-E2	Accelerate to 400 KCAS	240	400	240	430	300	11	1000	2860	5.7	5000	1.4	2.4	11
Climb-2	E2-E3	Climb constant CAS	400	400	430	760	572	119	2860	2740	2.9	36000	11.3	13.7	119
Climb-3	E3-E4	$\dot{h}^o/\dot{V}^o$ schedule to 530 KCAS	400	530	760	1000	775	329	2740	475	0.3	43750	16.3	30.0	329
Climb-4	E4-E5	Constant CAS to M 2.05	530	530	1000	1165	1120	559	475	660	0.2	51500	12.3	42.2	559
Climb-5	E5-E6	M 2.05 to RoC $\leq$ 200 fpm	530	520	1165	1165	1165	609	660	200	0.09	52300	2.5	44.7	609
Cruise	E6-E7	Cruise to start of decel.	520	450	1165	1165	1165	3029	200	$\leq$ 50	0.02	59000	124.0	208.7	-220
Decel./ Descent-1	E7-E8	Decelerate to 325 KCAS	450	325	1165	870	900	3059	-	-	0	59000	2.0	210.7	-190
Decel./ Descent-2	E8-E9	Descend to 3000 ft	325	325	870	330	500	3239	0	-2400	-5	3000	21.5	232.2	-10
Approach & Land	E9-Land		325	140	325	140	240	3249	0	-1200	-3	0	2.5	234.7	0

* Positive value indicates distance gone, while minus sign denotes distance to go to touchdown.

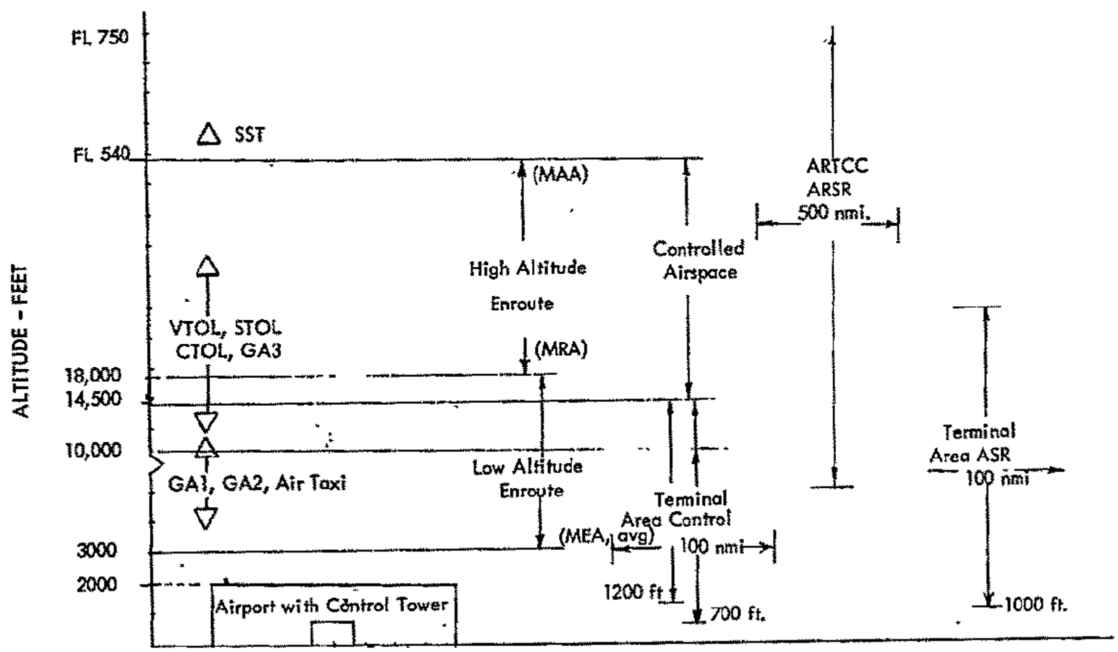


Figure 17. Surveillance and Control Region Summary

While the SST class of aircraft appears to be more complicated to operate than are present-day CTOL aircraft, extensive use of automation and technological advances incorporated in these vehicles should offset the complexity of the piloting task, and make flying them no more difficult than in the present-day CTOL jet. For a number of reasons, the SST class aircraft is expected to be permitted freedom from constraints on speed during the departure phase of flight. Thus expedited clearances were assumed for its departure.

The vertical profiles depict the point of penetration of terminal area altitudes by the air carrier users. It was assumed that the GA1 and GA2 aircraft maintained cruise altitudes within this terminal area envelope. Ten minutes elapsed time is utilized by CTOL and GA3 aircraft between penetration of the terminal area and the final approach and landing. This 10-minute period compares with the VTOL and STOL terminal area flight times of 12 minutes. The SST, if permitted a straight-in approach, would be in conflict with other traffic for only seven minutes of its final phases of flight; also, ATC requires less than one-half the time to handle the SST vehicle.

A summary of the aircraft flight regimes and the components of the ATC system is shown in Figure 17. Surveillance and control regions in terms of altitude and distance are indicated for enroute and terminal areas.

2.2.5 User Subsystems

A generalized airborne subsystem was structured to functionally integrate all classes of users. Figure 3 shows the flow diagram of the airborne system which was postulated to be functionally located in the cockpit in the proposed 1975 to 1985 time frame system. The functional flow diagram identifies the system information elements which are required by the pilot and/or ATC system on each phase of flight. The system will differ as regards number of elements as a function of the sophistication of the user. For example, it was assumed that general aviation aircraft such as GA1 and GA2 were not equipped for IFR flight,nor would they have access to such hardware as a navigation and guidance computer. The sources of information and signal paths are indicated and used to provide a reference for the area navigation, ATC, pilot control and pilot monitor functions.

Typical communication and navigation equipment are listed in Table XI.

With respect to future automation of the airborne system, significant omissions in current aircraft equipments are: the absence of a data link, lack of an area navigation system, and lack of small, low cost general purpose computers.

2.2.6 Surveillance Information Source

The advanced navigation system was required to meet two broad criteria. First, the systems had to meet the performance requirements set out for area navigation, approach and landing. Secondly, the system was required to provide surveillance information of sufficient precision and information content to replace the data derived from ground based radar. The area navigation system was configured around four candidate position determination systems and a DR system configuration.

(1) Navigational Satellite (NAV SAT)
(2) Ground Based Time Difference (GBTD or hyperbolic aids)
(3) VOR/DME
(4) Precision VOR/Precision DME (PVOR/PDME)
(5) Hybrid air data, doppler, and inertial systems dead reckoning (DR)

The approach and landing system requirement was evaluated with respect to five candidates:

(1) GBTD
(2) Differential GBTD
(3) Differential NAV SAT
(4) Coupled Instrument Landing System (ILS)
(5) Advanced Instrument Landing System (AILS)

TABLE XI
AIRBORNE NAVIGATION SYSTEM INSTALLATIONS

All include pilotage

USER		POSITION FIX	DEAD RECKONING			HOMING	ATTITUDE & HEADING	TO, APPROACH & LANDING
			Horizontal	Vertical	Heading			
General Aviation	GA 1	map read charts VOR	Air Data	Pressure Altimeter	Mag Compass	Comm/Nav 90 channel VHF VOR, LOC	Mag Compass AI	Comm/Nav R/T 90 Channel (LOC)
	GA 2	map read charts VOR	Air Data	Pressure Altimeter	Mag Compass	Comm/Nav VHF VOR/LOC, ADF	AI, Mag Compass	Comm/Nav R/T 360 Channel MBR, ADF, LOC
	GA 3	VOR/DME map read	Air Data Doppler	Pressure Altimeter Radar Alt.	Compass Mag/DG	Comm/Nav, VOR LOC, ADF	Mag Compass ADI, Vertical Gyro	Comm/Nav R/T 360 Channel MBR ADF, DME, LOC, GS
CTOL Jet	Long Haul	Loran A/C celestial map read VOR/DME	INS(2), Air Data Doppler	Pressure Altimeter Radar Altimeter	Compass Mag/DG	Comm/Nav VHF R/T (VOR, LOC) ADF	Attitude Reference Unit	Comm/Nav Transceiver, ILS (LOC, GS) DME, MBR, ADF
	Short Haul	VOR/DME	Air Data	"	"	"	"	"
VTOL	Helicopter	Decca Hyperbolic VOR/DME map read	Doppler Air Data	Radar Altimeter, Doppler Radar	Mag Compass	Comm/Nav VHF R/T (VOR, LOC) ADF	Vertical Gyro	
	Tilt Wing/ Lift Fan	VOR/DME map read	Air Data	Pressure Altimeter Radar Altimeter	ARU Mag Compass	Comm/Nav VHF R/T (VOR, LOC) ADF	Mag Compass Attitude Reference Unit	Comm/Nav Transceiver, ILS (LOC, GS), DME, MBR, ADF
STOL	Turbo prop	"	Air Data	"	Mag Compass Gyro	"	"	"
	Turbo fan	"	Air Data	"	"	"	"	"
SST		map read NAV SAT VOR/DME Loran C	INS(2), Air Data	INS, Radar Altimeter Pressure Alt	INS, Mag Compass	(VOR, LOC) Comm/Nav R/T	IRU Mag Compass	AILS, DME, INS

TABLE XII
USER CANDIDATE SYSTEMS - 1975-1985

USER	ENROUTE & TERMINAL AREA	APPROACH	LANDING
SST CTOL JET GA 3	DR + TD (NS) DR + TD (GB) Rho - Theta	DTD + DR DTD (NS), DTD(GB)	AILS, DTD, DR
VTOL STOL	DR + TD (NS) DR + TD (GB) Rho - Theta		DTD (NS), DTD(GB) MBR, PDME
GA 1, GA 2	TD (NS), TD (GB) Rho - Theta AIR DATA DR	Visual	Visual

The differential time difference system concept is described in Appendix F. Briefly, it is conceived as a system which permits the calibration of time difference signals within a limited service area, say a Terminal Area. A time difference receiver, located within a TMA, monitors the received NAV SAT or GBTD signals in that region, determines the necessary differential correction signals to reduce systematic errors to a very small value and then transmits calibration signals to the user vehicles operating in the area.

Table XII summarizes the various 1975-1985 candidate system techniques by user type. It will be noted that the navigation system candidates suggested for the SST, CTOL and GA3 user aircraft are the same. The VTOL and STOL landing system requirements are sufficiently different from the CTOL aircraft that significant differences in equipment are required. PDME and Marker Beacon Receivers (MBR) are added to the basic equipment fit specified for the CTOL vehicles. The GA1 and GA2 class of aircraft were assumed to retain their essentially VFR approach and landing system configurations but, as will be seen, uprated sufficiently to permit their integration into a completely controlled ATC environment.

The navigation system generates aircraft position data for subsequent link to the traffic control surveillance unit. The three link candidates are VHF voice communication, VHF digital data link and UHF digital data link.

The interaction of pilot, aircraft, airborne and ground based systems lead to the creation of several system configurations for each kind of user aircraft. These hybrid communication and navigation configurations stimulate the development of a number of system levels of automation which are evaluated for their contributions to reduction in workload (Section 6).

SECTION 3

DESIRED OPERATIONAL CAPABILITY

3.0 SUMMARY

This section presents the results of requirements analysis and summarizes the desired operational capability of the 1975 – 1985 navigation/ATC system.

The operational requirement is developed from a cockpit point of view. A requirement for an area navigation system which permits flexibility in the enroute and terminal areas is specified. Pilot workload is to be held to a minimum. Position and track keeping accuracies are specified as is the need for continuous airborne derived data for ATC surveillance. A reduction in communication workload is stipulated as is the need for VHF or UHF selective-call data link for surveillance reports and message acknowledgements. Voice communications are retained as a back-up information link. Finally an integrated airborne computer which interfaces with the area navigation, communication, and traffic control system is specified. Its purpose is to assist in reducing ATC intervention to a minimum, and permit rapid amendments to clearance with the objective being to minimize or eliminate delays.

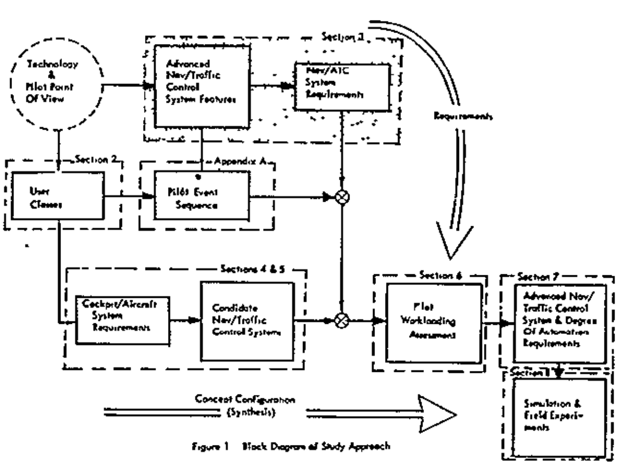


Figure 1 Block Diagram of Study Approach

The operational requirement, developed with the viewpoint of the pilot in mind, is expanded by adding the general area navigation operational requirement. Requirements on the system include: (1) that the system meet the user accuracy requirement, (2) that it be non-saturable, (3) line-of-sight independent, (4) flexible to ATC route structure and vector commands, and (5) provide area and volume coverage. The system should also operate with real time data rates, operate in all weather, and incur minimal costs in the ground station complex. Finally, the system must impose minimum workload on the pilot or copilot.

Other navigation system functions arise from the needs of the traffic control and surveillance system. The navigation system must generate ATC surveillance information; provide a holding capability and slant tracks; and incorporate the feature of waypoint vectoring. Pilot information needs, derived from the manual and/or automated navigation management function, are: track angle error, cross track distance, distance to go, altitude, altitude rate, and estimated time of arrival. The communications functions include: control, surveillance, and advisory messages. The control messages are the ground-to-air command data such as vector, vector waypoint sequence, speed scheduling, code changes, etc. The surveillance messages are air-to-ground and are initiated within the navigation system.

Advisory messages are identified as being both ground-to-air and air-to-ground.

The above system-level functions are quantified as navigation accuracy requirements, and communication system data requirements.

Navigation requirements, in terms of system 3 σ accuracy, are generated from six related sources: these are 1975 to 1985 traffic activity forecasts; flight plan control, separation standards; ATC surveillance needs; approach and landing criteria; all weather landing criteria; and radar surveillance data complement. The air carrier class of user has a requirement of 0.5 nmi (3σ) in both terminal area and enroute flight. The minimum general aviation requirement is 0.3 nmi to 0.5 nmi (3 σ). The horizontal position accuracy for landing requirement for VTOL aircraft is 25 ft.; for STOL it is 50 ft., and for CTOL it is 75 ft. These navigation equipment requirements must be insignificant with respect to flight technical errors, human blunders, and display instrumentation uncertainties.

The navigation system requirement is completed with specification of the 1975 - 1985 communication requirement. The communication system capacity requirement is based on message content, 1975 to 1985 traffic activity forecasts, and interrogation rates. Air carrier and general aviation messages vary in content from 66 to 165 bits. Air carrier and GA3 bandwidth requirements approximate the standard 1200 bits/sec, but general aviation GA1 and GA2 requirements exceed the current data link bandwidth. This 4000 bit/sec rate can be reduced through tradeoffs in code setting, ground system update, flight plan compliance, and channel allocation.

These factors, features, and requirements constitute the 1975 - 1985 ATC desired operational capability.

SECTION 3

DESIRED OPERATIONAL CAPABILITY

This Section outlines the desired operational performance capabilities of an advanced navigation and air traffic control system. It specifies the system functions of the navigation, communications, and traffic control systems.

3.1 GENERAL

The desired operational features or capabilities of an advanced navigation/air traffic control system were developed from careful assessment of a variety of inputs; these included: a review of pilot comments and recommendations expressed in the open literature and in discussions with the investigation team; an evaluation of required system capacity based on an extrapolation of forecast traffic densities; an analysis of aircarrier and general aviation requirements; a review of stated federal objectives regarding future utilization of the national airspace; and review of official industry expressions regarding future system requirements emanating from organizations such as ALPA, AOPA, ATA, EIA, etc.

3.1.1 Pilot's Viewpoint

Because of the orientation of this study to the cockpit point of view, comments and recommendations regarding desirable features of advanced navigation ATC systems were sought. These are summarized below:

(1.) Reduce cockpit workload in the terminal area. High workload associated with the arrival and departure phases of flight is caused by lack of route

flexibility, except when radar vectored; the necessity to enter holding patterns without prior warning; the requirement to accept changes to speed, altitude, direction, transponder code setting, and clearances with no advance notice. Congestion on voice communication channels further adds to workload.

(2) Permit off-airways operation. Allow direct flight between TMA's and increase flexibility in choice of routes. Provide a published set of path-stretching lanes which allow a pilot to meet an assigned time over a fix.

(3) Utilize speed scheduling and path stretching to minimize delays. Advise of intent to use delays early in the flight.

(4) Provide flexibility of route selection in departure and approach to include utilization of slant tracks and flight paths which bypass slower traffic.

(5) Increase ease with which a flight crew can change its flight plans.

(6) Provide information which will forecast the need for route changes.

(7) Decrease message turn-around time.

(8) Eliminate changes to flight path which require operation at altitudes above or below optimum (fuel) altitudes and/or place the aircraft near its operating limits.

(9) Return control of navigation to the cockpit.

(10) Provide positive position information when the aircraft is in a holding pattern, e.g. map display.

From these statements the following system functional requirements are summarized.

(1) Navigation. Provide flexibility of route selection, accuracy of position determination throughout the route structure, and complete, unambiguous position coverage throughout the flight envelope.

(2) Communication. Decrease communication workload; provide positive control of communications embodying a selective-call data link, and automatic direct communication and acknowledgement functions.

(3) Navigation, communication, traffic control. Permit pilot control of aircraft flight path within the bounds of an approved flight plan. Reduce ATC intervention to a minimum. Permit rapid clearance amendments; minimize or eliminate delays.

3.1.2 Desired Capability By Category of User

The desired navigation performance capability varies as a function of aircraft user and phase of flight. The vehicles considered in this study were grouped into three general sets: VTOL and STOL; CTOL jet, GA3, and SST; and GA1 and GA2. The performance capabilities were related to two phases of flight, enroute and terminal.

3.1.3 Off-Airways Navigation Capability

The desire for freedom to operate off-airways along a three-dimensional flight path, or slant track, and the requirement to supply navigation and ATC assistance to all classes of user aircraft leads to specification of the following desired system characteristics:

(1) Not user saturable. The system must be non-saturable with respect to three factors: (a) surveillance data is available to ATC upon demand; (b) position and guidance data must be an available output to the pilot from the airborne navigation system to enable him to maintain assigned flight path; and (c) the airspace should not be user-limited by reason of inadequate number of available tracks.

Enroute: Point-to-point direct routing should be an allowable procedure. Further, it should be possible to utilize as many tracks parallel to the direct route as may be required to accommodate all the users. The use of parallel tracks in an area navigation system configuration can increase system capacity by a factor of 10.

Terminal Area: The busy hour operations forecast for the combined general aviation and air carrier users will set the upper limit of required terminal area system capacity.

Approach and Landing: Use of positive control procedures for all aircraft can presently reduce required longitudinal separation during approach and landing to an interval of not more than two minutes. Use of speed scheduling, PWI and automated communications could reduce the interval to less than one minute, provided that taxi facilities are adequate. Continuous position data is necessary if VOR approaches are to be eliminated and if aircraft are to have direct access to rural terminals. Use of flow control techniques in the terminal area such as path stretching would be facilitated with area navigation.

(2) Frequency Protection. The postulated advanced navigation, approach and landing system should not be vulnerable to saturation or to over-

lapping of other facilities utilizing its frequency channels. Adjacent ground-based transmitters used to provide time difference signals, differential time difference signals, and NAV SAT derived time difference signals will require frequency protection.

(3) LOS Independent. Positive all-area control of communication, navigation and guidance data is mandatory. During flight in the terminal area and while enroute at low altitude in congested airspace, surveillance data must be linked to the surveillance unit of traffic control. The data link must be independent of LOS limitations for A-G and G-A transmission. Approach Control communication and navigation position coverage must extend from 1000 ft. to 14,500 ft. in the terminal area, an area approximately 100 miles in diameter in today's large hubs.

(4) Time independent. The transient and steady state errors of the position information must be less than the accuracy requirement for all phases of flight and for all aircraft maneuvers.

(5) Accuracy Constraints. The navigation system must meet the track-keeping, altitude-keeping, speed and ETA constraints set out in Section 3.5, independent of weather, topography, position relative to the navigation aids in use, or aircraft maneuver.

(6) All-weather. Accuracy of the area navigation approach and landing system must be maintained within the stipulated error for all-weather conditions. General aviation aircraft GA 1 and GA 2 were assumed to require the capability to operate in IMC conditions while enroute but not during approach and landing. The GA 3 aircraft was assumed to operate in IFR conditions to include CAT II landing minima.

(7) Real time operation. It must be possible for any user to interrogate the area navigation system at any time and as frequently as he requires. The provision of surveillance information to the ATC system from the aircraft requires that position information be continuously available.

(8) ATC Compatibility. Two requirements of the advanced navigation system, if it is to meet the 1975-85 ATC needs, are the airborne generation of surveillance data and the necessity for commonality in output format.

Generate ATC surveillance data. Within the limits of accuracy required by ATC, generate surveillance data such as aircraft identification, position, speed, track, altitude, time, and ETA next mandatory reporting point.

Common Output format. Terminal area and enroute flights operating under the surveillance of ATC on either an IFR or VFR clearance should be capable of reporting aircraft position in a format specified by ATC, i.e.,the format of the flight plan. The report should be available to ATC upon demand or according to fixed request, e.g., mandatory reporting point. Any necessary coordinate conversions should be performed in the airborne system. The system must be capable of accepting arbitrary revisions to flight plan, using automatically inserted waypoints.

(9) Cockpit Compatibility. Five of the desirable cockpit-related features of an advanced area navigation system are set out below. Details of each are expanded upon in succeeding paragraphs.

Flexible to ATC route structure and vectoring. Provide the means to alter the programmed route of flight by insertion of arbitrary waypoints dictated by ATC during both terminal area and enroute operation. The availability of a means to automatically up-link and insert a revised flight plan would significantly reduce communication workload. A means to review, approve or reject, and to acknowledge any revisions would be required.

Map reference. Aircraft position should easily be related to the intended or authorized route of flight, whether the aircraft is operating off-airways, on a published jet route, low altitude route or within a terminal area. System output of steering information, aircraft position, and flight plan information must be referenced to the established coordinate system and reference direction, e.g., lat/long, magnetic north, etc.

Permit positive identification of waypoint. Ensure that means are provided to assist the pilot in selection, identification and validation of waypoints.

Require minimum pilot workload.

Compatible with onboard subsystems. The area navigation, approach and landing system must meet the following requirement (10).

(10) Fail operational. The area navigation, approach and landing system must include a fail operational design, backup subsystems, or redundant units.

(11) Growth-oriented. The system capacity, reliability and maintainability should be developed about a growth-oriented, expansion-capable navigation system which can accept traffic capacities four times the present level of the New York Hub. The system capacity should be sufficient to permit all GA 1 and GA 2 aircraft to operate in accordance with the existent instrument flight rules of the 1975-85 system if they choose to do so.

(12) Physical constraints. The equipments must be low cost, small in volume, lightweight, require minimum power, and possess maximum maintainability and reliability.

(13) Summary of Desired Operational Capabilities. Table XIII below summarizes the desired area navigation operational capability.

TABLE XIII
GENERAL NAVIGATION OPERATIONAL REQUIREMENT

Non-saturable for Users	Minimal Number of Ground Stations
LOS Independent	All-Weather (IMC)
Flexible to ATC Route Structure/Vectoring	Real Time Operation
Avoid Frequency Saturation	Growth Oriented
Area Coverage	Flight Path Adaptive
Time Independent	Generate ATC Surveillance Data
Map Reference	Compatible with Onboard Subsystems and Pilot Information Needs
Common Output Format	Satisfy Accuracy Constraint
Fail Operational	Minimum Pilot Workloading

3.1.4 Navigation/CCC (Communications, Command and Control) Operational Requirement

(1) General Requirement. The following general navigation functions are based on traffic control and surveillance needs.

- Commonality. Generate position reports, data for position reports, flight plan data, and vector acknowledgement in a common navigation, traffic surveillance format.
- Adaptive compatibility. Because of user economics or aircraft equipment sophistication, the ATC system might be required to talk to different navigation systems. For example, GA 1 and GA 2 might use a course line computer in conjunction with VOR/DME, while other users would employ time difference, and differential time difference systems.
- Interface to ATC surveillance unit. Interface data link or voice with ATC surveillance and control unit.
- Provide holding capability. Need fixed waypoint and holding routine.
- Provision for waypoint vectoring. Adapt system for waypoint vectoring, insertion of leg start points and end points.
- Automatic reporting. Aircraft standard report supplied on interrogation at any time; therefore, a system which results in position fixing at infrequent intervals will require a hybrid dead reckoning capability.
- Supplement radar surveillance data. The navigation system position, heading and altitude information can be used to complement ground based radar-generated data.

Table XIV summarizes the navigation/traffic control system general operational requirement.

TABLE XIV ATC-RELATED NAVIGATION FUNCTIONS

Commonality and Ground Use of Data
Interface to ATC Surveillance Unit
Respond to Traffic Control Unit
Provide Holding Capacity
Provide Slant Tracks
Provide for Waypoint Vectoring
Automatic Reporting
Supplement Radar Surveillance Data per Flight Phase
Tactical Flight Control

(2) Summary of Causes of Delays and Their Solution.

- Causes of Delays. Reference 5 itemizes and discusses causes of delays in Terminal Areas. These include weather, runway capacity limitations, approach and departure routes, limited ramp space, enroute capacity limitations and aircraft scheduling. The major causes are stated to be runway

Ref. 5 - Alternative Approaches for Reducing Delays, N68-12177, Nov 67

capacity limitations, limited approach and departure routes, and limited airspace and capacity outside the immediate terminal area.

- Solutions to Delays. Reference 5 pinpoints a number of solutions not related to modification of airports or construction of new ground-based facilities such as airport expansion and the design of high speed taxi-ways which were found to effectively increase system capacity.

- Procedural Changes and automation of the final approach spacing function:

  - Reduced radar spacing offers gains of up to 40% but requires continual, accurate surveillance contact.

  - Significant gains in IFR capacity can be achieved by reducing the requirement from a three-mile to a two-mile interval between aircraft operating under radar surveillance for parallel runways separated by less than 5,000 feet.

- Use of Multiple or dual approach paths.

- Use of tighter schedule control.

- Use of additional approach and departure routes facilitated through the use of course line computers and pictorial displays.

- Develop automatic landing and departure system for safe,

expeditious handling of multiple (not same runway) operations.

- Interlace operations (with respect to aircraft) in optimal fashion.

- Additional Procedures. In addition to the use of new terminal procedures described above, other operational solutions to traffic congestion include the following procedures:

  - Delay clearances; delaying departure clearances
  - Utilize stacks and holding patterns at clearance limits
  - Vector to uneconomical flight regimes
  - Path stretching, speed control and rerouting
  - Withhold clearances to select users per equipment classification.

(3) Summary. An area navigation, approach and landing system coupled to an airborne surveillance link should supply the capability summarized in Table XV, below.

TABLE XV
OPERATIONAL CAPABILITY TO INCREASE SYSTEM CAPACITY

Accurate surveillance data for all (IFR and VFR) Aircraft, in all weather conditions, in all terminal areas must be supplied to the surveillance unit.
Multiple and flexible approach paths.
Multiple access routes, direct approach and departure routes in the terminal area.
Positive communications control on voice or data link.
Refined aircraft position increases capacity cheaply.
Priority mixing of departure and arrivals is a necessary planning function.
Incorporate automation in processing the navigation data for the clerical ground tasks.

3.2 PILOT INFORMATION NEEDS

Appendix A presents a detailed description of the pertinent information needs for the traffic control communication, navigation, and aircraft control tasks in domestic airspace. The complete array of pilot information needs for use in defining the airborne systems for each class of user is presented in Appendix B. The pilot information needs are identified with respect to navigation and communication management functions. Appendix A relates these information needs into the proper sequence within the flight profiles.

3.2.1 Navigation Management Function

The pilot/navigation information needs are derived from the navigation management function, which is comprised of the following essential tasks: system initial set up; review meteorological forecast; inflight system program; inflight system reprogram; steering data acquisition; flight path status check; flight plan status check; and report preparation. The tasks, dependent upon the user and the user avionics, may or may not be automated.

Table XVI presents the information needs of the pilot in performing the navigation management function. The data are summarized from Appendix B. Generally, the information content as presented in this Table is information required for IFR flight in controlled airspace and applies equally to all classes of pilots - from general aviation to SST. The information needs presented in Table XVI also pertain to GA 1 and GA 2 pilots operating in controlled airspace under VFR conditions. Section 6 describes the tradeoffs between system-levels of automation and system configurations required to satisfy specified pilot information needs.

The minimum user information needs for VFR flight in uncontrolled airspace, for example those of the GA 1 and GA 2 pilot, are suggested to be distance and bearing to desired waypoint, navigation aid or reference point.

TABLE XVI
INFORMATION NEED SUMMARY - NAVIGATION FUNCTIONS

Navigation Management Function	Flight Phase		Pilot Information Need Derived from Input	Input
	Terminal	Enroute		
Review Met Forecast	X	X	wind along track component wind cross track component	G-A comm. - wind direction, wind speed, temperature, pressure, visibility
Review Current Track	X	X	desired track distance to go desired track distance to go	ground facility - range, bearing, mag heading, flight plan waypoint (wpt.) - wpt. lat., wpt. long, aircraft lat., aircraft long., mag. heading, flight plan
Update Steering	X	X	track angle error track angle error track angle error	traffic control vector - drift angle, mag. heading flight plan track - range, bearing to facility, drift angle, mag. heading flight plan track - wpt. lat., wpt. long., aircraft lat., aircraft long., drift angle, mag. heading
Flight Path Status Check	X	X	cross track distance ground speed estimated time of arrival altitude rate altitude	elapsed time, true airspeed, along track wind, mag. heading, drift, distance to go, pressure altitude, desired track
Flight Plan Status Check	X	X	distance to go cross track distance estimated time of arrival ground speed altitude fuel remaining	flight plan, throttle setting, pressure, density, airspeed, wind along track, elapsed time, fuel capacity

3.2.2 Communications Management Function

The pilot/ATC information needs are derived from the communication management function. Appendix B presents the detailed analysis of the communication management functions for the candidate user aircraft examined in this study.

The pilot information needs for interface with the traffic control system are seen to include the data used in the standard report and the abbreviated report. Variations in message content will depend upon the system-levels of automation. These are discussed more fully in Section 6.

(1) Air Carrier and GA3 Users. The standard report presently contains the following pilot-generated information: aircraft identity, position (latitude, longitude, waypoint or range and bearing from a specified facility), time, altitude, ground speed, heading*, destination (latitude, longitude, name of airport) or next waypoint and estimated time of arrival thereat.

The present abbreviated report contains the following information: aircraft identity, time, position and altitude. In the advanced automated systems suggested in this study, the abbreviated report is simplified into aircraft identification, time, and an acknowledgement that the stored flight plan and the present aircraft state (position, altitude, speed, fuel remaining, etc.) are in agreement.

(2) General Aviation GA1, GA2 Users. The standard report is to be modified in the proposed advanced system, as a function of the system-levels of automation. Various formats are discussed in Section 6. Specific message content will depend upon the level of system automation. Section 6 also discusses a last-resort general aviation system for GA1 and GA2 class of users which relies upon ground-based computation of aircraft position. The up-link on the traffic control system thus contains primary information needed by the pilot, e.g., distance and required course to destination.

3.3 ADVANCED NAVIGATION/TRAFFIC CONTROL FEATURES

The communications, command and control system is intended to perform the three major functions of control, surveillance and advisory services.

3.3.1 Ground-to-Air Communications (G-A)

* Enroute track is substituted for heading

(1) Control. Control of traffic is dependent upon Command, and Confirmatory or Request for Information messages.

Command Data - these G-A communication items include:

- Enroute or terminal area track or waypoint sequence change
- Vector, track change, or hold point
- Speed change
- Altitude change
- Frequency change
- Code change
- Aircraft Identification
- Clearance amendment, and
- Clearance delivery.

Confirmation and Request - return messages include:

- Message acknowledgement
- Control unit identification
- Request direct communication

(2) Advisory Service. The ground-based communications, command and control system supplies hazard avoidance service through the following advisories:

Traffic advisory, a message which identifies the proximity of an aircraft hazard; and, if known, its speed, range, bearing and altitude from the advised aircraft.

Meteorological data advisory, a message which contains information about winds, temperature, turbulence and SIGMET occurrences, and current altimeter setting.

(3) The Air Terminal Information Service provides information about wind direction and speed, altimeter setting, runways in operation, unusual NOTAMS, known traffic, airport traffic routes, airport traffic patterns,

and instrument approach procedures. All data is relative to destination or departure terminal.

(3) Surveillance. The airborne navigation system is assumed to generate the required surveillance data which it reports upon interrogation from the ground system or when the aircraft arrives over specific points set out in the flight plan. The specific points will include mandatory reporting points (unless the ground surveillance unit advises to omit reports), altitudes or flight levels of significance in descent, and certain terminal area, final-approach, waypoints.

Standard report. The standard report could include aircraft identification, position (latitude, longitude; waypoint identification, range and bearing; time difference values (GA 1, GA2), time, altitude, ground speed, heading, next waypoint (latitude, longitude; or code), ETA.

Abbreviated report (a). This abbreviated report could include aircraft identification, flight plan status, and time.

Abbreviated report (b). A second type of abbreviated report, for use in congested airspace where frequent interrogations are likely to occur, could include aircraft identification, position, and altitude.

3.3.2 Air-to-Ground Communications (A-G)

(1) Control. Because of contingencies which arise in flight, a pilot will always require the ability to modify his flight plan. The following semi-automatic man-computer-comm link Air-to-Ground (A-G) communications capability will therefore be required.

Request terminal or enroute track or waypoint change
Request vector or track change

- Request speed change
- Request altitude change
- Request destination change
- Confirm clearance amendment
- Message acknowledgement
- Aircraft identification
- Request direct communication

(2) Advisory. The present air-to-ground advisory voice link on which are transmitted significant meteorological observations such as severe turbulence, icing, precipitation, cloud, etc. should be retained.

3.4 NAVIGATION SYSTEM OF REFERENCE

The advanced navigation/traffic control system requires a defined coordinate reference system. The two systems of reference are the geometric system used in defining vehicle position, and the analytic system utilized in describing vehicle attitude. The geometric system is the basic coordinate system used for computation of vehicle location. The analytic system is the coordinate reference against which vehicle attitude, velocity, or acceleration is measured by the navigational sensors.

3.4.1 Geometric and Analytic System - Enroute

At altitudes above 18,000 feet all aircraft would use the geometric system of geocentric latitude, longitude, combined with pressure altitude, where pressure altitude is measured with respect to the standard datum plane, 29.92 inches Hg. Below FL 180, altitude would continue to be measured relative to the current local altimeter setting. The analytic system of reference would be a local vertical, magnetic north, east system, throughout the flight profile.

3.4.2 Geometric and Analytic System - Terminal Area

Because the high proportion of general aviation aircraft operate at altitudes which are identical with those used by all aircraft departing or arriving at a terminal, and because these aircraft do not possess a true north directional reference capability, the recommended analytic system of navigation is a local vertical, magnetic north, east system. The geometric system for all users is a latitude, longitude, pressure altitude reference system. The latitude, longitude system ties together the waypoints, landmarks, airfields, and ground facilities on the aeronautical chart and/or low altitude enroute chart. The general aviation pilot defines position in terms of range and bearing from these ground points. Thus the basic system of reference is the latitude, longitude system.

3.4.3 Pilot Reference - Terminal Area

Constant need for orientation in the terminal area for all classes of users requires that identifiable points in the terminal area be coded and specified on all pictorial displays and local aeronautical charts. The specific code techniques will be defined from operational experience, but the coded points should be referenced to the geometric system of reference - all points are tied to the geocentric latitude, longitude, and altitude system.

Terminal area coded points, as examples, would be final approach waypoints, selected ground facilities or fixes and intersections, and identifiable waypoints specifying recommended departure and approach tracks.

3.5 NAVIGATION SYSTEM REQUIREMENTS

Navigation requirements, in terms of system 3σ accuracy, have been generated from six related sources:

(1) traffic activity forecasts
(2) flight plan control (ETA)
(3) separation standards and ATC surveillance needs
(4) approach and landing criteria
(5) all weather landing criteria
(6) radar surveillance data complement

The navigation accuracy constraint is given in terms of vector

$$\begin{bmatrix} \sigma_{AT} \\ \sigma_{CT} \\ \sigma_{h} \\ \sigma_{A} \end{bmatrix}$$

where

σ_{AT} = 3σ along track error

σ_{CT} = 3σ cross track error

σ_{h} = 3σ altitude error

σ_{A} = 3σ heading error.

The navigation equipment accuracy constraint is specified by the above vector. Throughout the derivation of the navigation requirements, the along track, cross track and altitude components are derived from the following equations:

$$\sigma_{AT} = 1/10 \; s_{AT}$$

$$\sigma_{CT} = 1/10 \; s_{CT}$$

* Note: See List of Symbols and Nomenclature, pages xviii and xix, for a listing and definition of these 3σ values, used hereinafter in all Tables and discussions.

$$\sigma_h = 1/10 \; s_h$$

where

s_{AT} = an along track distance

s_{CT} = a cross track distance

s_h = an altitude.

The 1/10 factor is used to define navigation equipment errors which will be insignificant with respect to:

(1) flight technical errors
(2) human blunders
(3) display instrumentation, control, and guidance errors

This constraint was made significantly stringent so that the requirements would be maximum, and safety factors could be incorporated.

The methodology which was used to derive the system requirements is documented in Appendix C.

3.5.1 Navigation Requirements – Summary

A summary of the 1975 - 1985 navigation requirements is tabulated in Table XVII. These minimal accuracy constraints specify the 3σ horizontal accuracy needs for the navigation systems of SST, CTOL, VTOL, STOL and general aviation aircraft. As noted in Table XVII, the requirement varies with respect to flight phase. Generally, the air carrier class of user has a requirement for 0.5 nmi (3σ) throughout terminal area and enroute flight. The general aviation minimum constraint is 0.3 nmi (3σ) to 0.5 nmi (3σ). The lower 0.3 nmi general aviation requirement results from the reduced speeds of GA1 and GA2 aircraft.

VTOL and STOL aircraft requirements are nearly identical to those of the CTOL and SST aircraft. The horizontal accuracy requirement for VTOL aircraft during landing was determined to be 25 ft (3σ); for STOL, a 50 ft requirement was determined; and for CTOL a 75 ft requirement was determined.

TABLE XVII
SUMMARY - MINIMUM HORIZONTAL ACCURACY REQUIREMENT IN CONTROLLED AIRSPACE, 1975-1985

AIRCRAFT / FLIGHT PHASE	IFR AND VFR					VFR FLIGHT PLAN REFERENCE	
	SST	CTOL JET	VTOL	STOL	GA3	GA2	GA1
TAXI	35 ft	35 ft	15 ft	25 ft	35 ft	NA	NA
TAKE-OFF	35 ft	35 ft	15 ft	25 ft	35 ft	NA	NA
CLIMB-OUT	0.5 nmi	0.5 nmi	0.5 nmi	0.5 nmi	0.5 nmi	0.3 nmi	0.3 nmi
ENROUTE - LOW	0.5 nmi	0.5 nmi	0.5 nmi	0.5 nmi	0.5 nmi	0.5 nmi	0.5 nmi
ENROUTE - HIGH	1.6 nmi	0.5 nmi	0.5 nmi	0.5 nmi	0.5 nmi	NA	NA
ARRIVAL	0.5 nmi	0.5 nmi	0.5 nmi	0.5 nmi	0.5 nmi	0.5 nmi	0.5 nmi
DESCENT	0.5 nmi	0.5 nmi	0.5 nmi	0.5 nmi	0.5 nmi	0.3 nmi	0.3 nmi
APPROACH	360 ft	360 ft	360 ft	360 ft	360 ft	0.3 nmi	0.3 nmi
LAND - CAT II	75 ft	75 ft	25 ft	50 ft	75 ft	NA	NA
LAND - CAT IIIC	15 ft	15 ft	15 ft	15 ft	15 ft	NA	NA
TAXI	35 ft	35 ft	15 ft	25 ft	35 ft	NA	NA
HOLDING	0.12 nmi	0.12 nmi	0.12 nmi	0.12 nmi	0.12 nmi	0.12 nmi	0.12 nmi

The paragraphs which follow summarize the navigation accuracy requirements.

3.5.2 Traffic Activity Forecast

Navigation requirements were computed from three traffic activity forecasts. Table XVIII, below, summarizes general aviation and air carrier navigation requirements which were calculated from three forecast types:

(1) 1985 peak minute density (overs, departures and arrivals) per 100 square nmi

(2) 1985 peak minute densities (overs, arrivals, departures) under surveillance per ATC center..

(3) 1980 peak hour operations (arrivals, departures) within a Large Hub.

TABLE XVIII
NAVIGATION ACCURACY REQUIREMENTS - TRAFFIC ACTIVITY FORECASTS

Activity Forecast	General Aviation GA1, GA2			Military and Air Carrier GA3, CTOL, VTOL, STOL					
	Altitude: 6 kft - 11 kft			Altitude 11 kft - 18 kft			Altitude 18 kft - 39 kft		
** → 3 σ values	σ_{CT} nmi	σ_{AT} nmi	σ_{AT} min.*	σ_{CT} nmi	σ_{AT} nmi	σ_{AT} min.	σ_{CT} nmi	σ_{AT} nmi	σ_{AT} min.
Peak Minute Density per 100 sq. nmi	0.3-1.0	1.5	5.0	0.4	2.5	5.0	1.0	5.0	15
Peak Minute Density per center (arrivals, departures, overs)	0.14-0.45	1.5	5.0	0.6-0.8	2.5	5.0	0.4-0.7	5.0	15
Peak Hour Density per Hub (arrivals, departures, overs)	0.18-0.83	1.5	5.0	0.7-5.0	2.5	5.0	0.5-6.0	5.0	15
Nominal Range Summary	0.2-1.0	1.5	5.0	0.5-5	2.5	5.0	0.5-6.0	5.0	15

*minutes

A complete discussion of the methodology employed in construction of Table XVIII is contained in Appendix C, Section C.1.

The navigation requirements are:

General aviation GA1, GA2

$$\sigma_{AT} = 1.5 \text{ nmi, } 5 \text{ minutes}$$

$$\sigma_{CT} = 0.2 \text{ to } 1.0 \text{ nmi}$$

Military and Air Carrier (low altitude)

$$\sigma_{AT} = 2.5 \text{ nmi, } 5 \text{ minutes}$$

$$\sigma_{CT} = 0.5 - 5 \text{ nmi}$$

Military and Air Carrier (high altitude)

$$\sigma_{AT} = 5.0 \text{ nmi, } 15 \text{ minutes}$$

$$\sigma_{CT} = 0.5 - 6 \text{ nmi}$$

3.5.3 Flight Plan Control

The coordination between the aircraft flight profile and the advanced traffic control system is given in terms of estimated time of arrival at a fixed waypoint either enroute, in the terminal area, or in a holding pattern. The pilot complies with the flight plan by monitoring ETA to the next waypoint. The traffic control system employs surveillance data to estimate the aircraft arrival at the assigned waypoint. When the traffic control system employs airborne derived surveillance data and ground based computer flight plan data, ETA is the variable which measures system performance.

Errors in the variables which are used to compute ETA identify the system requirements. By specifying the tolerance on ETA which is acceptable to the traffic control system for safely controlling the flow of traffic, system requirements can be derived.

The four geometric systems which may be employed by user aircraft are the rho-theta system, along track/cross track system, rhumb line, and the great circle system. These coordinate systems generate, with suitable signal processing, aircraft steering signals for control of the aircraft in the horizontal plane. Conventional guidance signals which the pilot uses to update the aircraft steering signal are cross track distance and track angle error. These guidance signals are relative to a desired track. To further determine the aircraft status along a given track, the pilot requires knowledge of distance to go. To comply with a flight plan, the estimated time of arrival at the next waypoint is then computed from distance to go, ground speed and present time.

The ETA requirement, speed, along track, cross track requirements are summarized in Table XIX.

3.5.4 Separation Standards and Surveillance Needs

Navigation requirements can be derived from traffic control separation requirements. The FAA establishes separation requirements throughout all controlled airspace, from terminal area departure and arrival to holding patterns and enroute airspace. The separation factors depend upon whether traffic is converging or diverging; whether traffic is crossing same altitude levels; and relative speeds of same-track aircraft. Separation requirements, expressed in terms of cross track separation (nmi), along track separation (minutes), and altitude separation (ft) are translated into navigation accuracy requirements by applying the 1/10 ratio. Those requirements in terms of time become navigation requirements if the vehicle speed is known.

Separation requirements have evolved from an existing, safe system. In Section 3.1.4 , (2), it was pointed out that a number of operational procedures can be utilized to increase system capacity.

Table XX summarizes the navigation requirements as derived from consideration of separation criteria. Along track, cross track and altitude requirements are tabulated.

TABLE XIX
NAVIGATION SYSTEM REQUIREMENTS - FLIGHT PLAN CONTROL

USER	USER REQUIREMENT *				
	ΔETA minutes	σ_{CT} nmi	σ_{AT} nmi	σ_{A} deg.	σ_{V} percent
GA1, GA2	0.6	0.5	0.5	1.4	6.7
GA3, CTOL Jet VTOL, STOL, SST (Low altitude enroute) *	0.33	0.5	1.1	0.8	2.2
GA3, CTOL Jet, VTOL, STOL (High altitude enroute)	0.33	0.5	2.3	0.8	2.2
SST	0.33	1.6	4.4	0.15	0.8

*Also for terminal area with Alt. < 10,000 ft

TABLE XX
NAVIGATION REQUIREMENT - SEPARATION CRITERIA STANDARD AND SURVEILLANCE INFORMATION NEEDS

Separation Factor		Approach						Enroute						Departures/Arrivals							Holding	Minimum Summary
		3 nmi., max AT radar sep.	2 nmi., min AT radar sep.	AILS CT at 15 nmi ± 0.6 nmi	ILS CT at 20 nmi ± 3.3 nmi	AILS Alt. at 15 nmi ± 400 ft.	ILS Alt. at 10 nmi ± 400 ft.	15 min. AT (high & Lo Alt.)	16 miles CT (high Alt)	60 miles CT (oceanic)	5 miles CT (lo Alt)	500 ft., below FL 290	1000 ft., above FL 290	5 min AT, when crossing altitude levels	5 min AT, lead aircraft $\Delta V > 20$ knots	3 min AT, lead aircraft $\Delta V > 40$ knots	3 min, Divergent heading	1 min, Divergent landing with positive CT Sep.	10 nmi, altitude levels crossed	5 nmi, divergent tracks	From airways and other enroute traffic 5 nmi, 500 ft	* σ_{AT}, σ_{CT} σ_h
GA1 GA2	σ_{AT}							3.8			0.5			1.2	1.2	0.8	0 8	0.3	1.0	0.5	0.5	0.3
	σ_{CT}			visual										0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	σ_h											50	100	50							50	50
GA3 CTOL Jet VTOL STOL	σ_{AT}	0.3	0.2					7.5						2.5	1.2	1.5	1.5	0.5	1.0		0.5	0.2
	σ_{CT}			0.06	0.33				1.6		0.5			0 5	0.5	0.5	0.5	0 5	0.5	0.5	0.5	0.06
	σ_h					40	40					50	100	50							50	20
SST	σ_{AT}	0.3	0.2					30						2.5	1.2	1.5	1.5	0.5			0.5	0.2
	σ_{CT}			0.06	0.33				1.6	6 0	0.5			0 5	0.5	0.5	0.5	0.5			0.5	0.06
	σ_h					40	40					50	100	50							50	40

σ_{AT} in nmi, σ_{CT} in nmi, σ_h in ft.

* Note: See List of Symbols and Nomenclature, pages xviii and xix, for a listing and definition of these 3σ values.

3.5.5 Approach and Landing Criteria

Requirements on the navigation system can be derived from an evaluation of approach and landing accuracy criteria. As a minimum, the navigation system must provide sufficient accuracy in knowledge of position and speed to permit the pilot to fly the aircraft to a point where the landing aid is captured. The envelope of achievable trajectories leading to the point where the aircraft can capture the landing aid then defines the bounds of acceptable cross-track, altitude and rate errors. These requirements on the approach aid become tighter if the accuracy of the navigation system must meet landing accuracy criteria as well. The signals in both cases must be of a form suitable for interface with the automatic flight control system.

Table XX summarizes the navigation requirements generated by the approach constraint.

3.5.6 All Weather Landing Criteria

Position and velocity accuracy requirements on the navigation system can be derived from the all-weather landing criteria and assumptions about aircraft size and maneuver capabilities. The legal minima for instrumented runways specify runway visual ranges and decision heights for all-weather landing. The runway visual ranges and decision heights can be translated into along track navigation requirements; the decision height into altitude requirements.

Table XXI summarizes the all-weather landing requirements used in this study.

3.5.7 Taxiway Criteria

Navigation requirements can be derived from taxiway widths. Taxiways for CTOL, STOL, SST and GA3 are 75 ft wide. The taxiway in a vertiport is predicted to be 50 ft wide.

The navigation requirements for the taxiway criteria are also tabulated in Table XXI.

TABLE XXI
NAVIGATION REQUIREMENT - ALL WEATHER LANDING CRITERIA

		Landing						Taxi	Approach	
		Cat I	Cat II a	Cat II b	Cat III a	Cat III b	Cat III c		ILS σ_A	AILS σ_A
GA1, GA2 (not used in less than 5 n mi RVR (IMC)		NA	NA	NA		NA		NA		
GA3	$*\sigma_{AT}$ $*\sigma_{CT}$ $*\sigma_h$ σ_A	260 75 20 1°	160 75 20 1°	120 75 10 1°		NA		35 35 - 1°		
CTOL Jet**	σ_{AT} σ_{CT} σ_h σ_A	260 75 20 1°	160 75 20 1°	120 75 10 1°	70 75 0	15 75 0 1°	0 75 0		0.1°	0.03°
VTOL	σ_{AT} σ_{CT} σ_h σ_A	25	25	25	25	25	25	15 15 - 1°		0.03°
STOL	σ_{AT} σ_{CT} σ_h σ_A	50	50	50	50	50	50	25 25 - 1°	0.1°	0.03°
CTOL Jet & SST	σ_{AT} σ_{CT} σ_h σ_A	75	75	75	75	75	75	35 35 - 1°	0.1°	0.03°

*All units in ft.
**σ_{AT}, σ_A, σ_h hold for VTOL, STOL, CTOL Jet & SST

TABLE XXII
NAVIGATION REQUIREMENT - COMPLETE RADAR SURVEILLANCE

	Ground Unit Taxi In, Taxi Out, To Departure	Terminal Area Unit* Departure, Air Route (Lo), Appr, Stack Unit, Final Appr.			Air Route Unit* Air Route, Stack (continental)			Minimum Summary
		10 nmi	20 nmi	50 nmi	50 nmi	100 nmi	200 nmi	
GA1, GA2	NA	0.35	0 70	1.8	1.8	3.6	7.2	0.35
GA3, CTOL SST	0.43% @1.4 nmi = 36 ft	0.35	0.70	1.8	1.8	3.6	7.2	0.35
VTOL	0.43% 4 ft	0.35	0.70	1.8	1.8	3.6	7.2	0.35
STOL	0.43% 20 ft	0.35	0.70	1.8	1.8	3.6	7.2	0.35

*All units in nmi

3.5.8 Accuracy Relative to Surveillance Radar

Navigation requirements can be derived from the accuracy attained by surveillance radars. As a minimum, an advanced area navigation traffic control system would supplement the radar surveillance data with the airborne derived aircraft position data. Such a service would afford completeness in coverage for varying weather conditions and varying cross sectional areas. The radar surveillance data, range and bearing, must be converted to position information in the aircraft geometric system of navigation. The position accuracy is the navigation requirement.

Table XXII summarizes this navigation requirement.

3.6 COMMUNICATION SYSTEM REQUIREMENTS

The communication system requirements were derived from an estimate of expected traffic and system capacity. A VHF or UHF carrier was assumed as the transmission link.

The data link and voice link between airborne and ground systems must relay messages at specific instants in the aircraft flight profile. The voice link must always be available for direct communication between air and ground during the approach and landing phase. Workload would be affected significantly only when conditions are such that the percentage of pilot utilization is high. The conditions when these message reports occur are shown in the system operational flow diagram (see Appendix A).

Although it is beyond the scope of this program to determine communication system trade-offs, several well-understood assumptions have been employed. Binary coding was assumed because of the compatibility with ground based and airborne computers. Although modulation techniques such as Frequency Shift Keying (FSK) can provide the most beneficial S/N ratio in the link, current VHF modulation techniques and current signal power are sufficient for domestic operations. The frequency response of VHF modulation is 10 kHz, and this bandwidth is sufficient for air carrier and general aviation messages.

The data link requirement is bounded by the analysis of Appendix C, Section C.3. The analysis evaluates peak number of aircraft under control, sampling rates for the user, and poses tradeoffs in reducing the sampling rate.

Message content and system capacity requirements are summarized in the following sections.

3.6.1 Message Content

Message content is defined in terms of data words per message, bits per word and bit rate. The Flight Plan Reference ATC concept (see Section 4) is assumed for all aircraft.

(1) Standard Data Block

	Alpha Numerics	Digits	Bits
Aircraft Identity	7	-	20
UAL 213			
Cessna 7			
Position			
Option 1			
Latitude - N/S 60.432°	1	5	19
Longitude - E/W 126.432°	1	6	20
Option 2			
Waypoint	7		20
Range - 200.2		5	16 - (16) - (13)
Bearing - 271.6		4	12 - (12) - (9)
Time -23.42 hours		4	12*- (12)**- (8)***
Actual Altitude - 65.2 (1,000		3	10 - (9) - (7)
Ground Speed - 1300 kts		4	11 - (10) - (8)
Heading - 271.6 (true; magnet		4	12 - (12) - (9)
Waypoint			
Option 1			
Latitude - N/S	1	5	19
Longitude - E/W	1	6	20
Option 2			
Coded Waypoint	7		20
ETA - 23.62		4	12 - (12) - (8)

*SST; **VTOL, STOL, CTOL, GA3; ***GA1, GA2

The summary of the standard report data requirements is shown in Table XXIII. All messages include 11 data words. The general aviation message requires 122 bits for option 2 and 145 bits for option 1. The air carrier data message requirement is approximately 160 bits.

The full standard report is generally an enroute message. In congested airspace, the waypoint and ETA data words can be omitted. The bit count and number of data words is reduced. The word count is nine. General aviation bit count is reduced to 98 for option 1 and to 94 bits by reporting option 2. The air carrier bit content is reducec to approximately 110 bits. The following abbreviated report message reduces the bit count for general aviation by a factor of 50% to 66 bits.

(2) Abbreviated Report - Minimum Cost GA User

	Alpha Numerics	Digits	Bits
Aircraft Identity - N number	7	-	20
*Time Difference, TD1 - 555.6		5	11
*Time Difference, TD2 - 440.2		5	11
Altitude - 9.1 (1,000 ft)		3	7
Ground Speed - 180 kts		4	8
Heading - 271.6		4	9

Data Words: 6; Bits: 66.

*Typical range of value using a LF-CW hyperbolic system. Pulsed LF systems with greater range use 13 bits; 17 bits with coding delay of 50,000 μs. Long range VLF CW systems would require 16 bits.

(3) Abbreviated Report

This report is filed at the conditions (1) waypoint (DTG = 0) and not mandatory, (2) at tolerance limit DTG = 0, or (3) upon interrogation in congested airspace.

	Alpha Numerics	Digits	Bits
Aircraft Identity			
UAL 213 or N number	7	-	20
Abbreviated Report - MOK	3	-	9
Time - 23.42	-	4	12

Data Words: 3; Bits: 41.

(4) Request for Direct Communication

	Alpha Numerics	Digits	Bits
Aircraft Identity - UAL 213	7	-	20
Request Code - RED	3	-	9
Time	-	4	12

Data Words: 3; Bits: 41.

(5) Flight Plan

Transmitted on initial or amended clearance.

Data Transmitted - Flight Plan

Options: (1) Voice and Pencil Record; (2) Teleprinters.

		Alpha Numerics	Bits
1.	Type of Flight Plan (IFR/VFR)	3	2
2.	Aircraft Identification	3	20
3.	Radio Identification	4	2
4.	Flight Identification	3	20
5.	Type of Aircraft	4	10
6.	Time of Departure	-	12
7.	Aerodrome of Initial Departure	3	14
8.	Route to be followed (8 waypoints)	4 per WPT	18 per WPT
9.	Aerodrome of Intended Landing	3	14
10.	True Airspeed		11
11.	Cruising Level		10
12.	Estimated Time Enroute for each Route Segment		12 per WPT
13.	Alternate Aerodrome		14
14.	Estimated Total Time Enroute		12 per WPT
15.	Fuel Endurance		16

Bits: 187

Pilot Clearance Record - ATC Control Function

Recording options: (1) pilot shorthand; (2) alpha numerics.

	Pilot Designation	Meaning
1.	C	Clears or Cleared
2.	R	Range
3.	APP	Approach Control
4.	Z	Tower

	Pilot Designation	Meaning
5.	A	Aerodrome
6.	↑	Climb to (FL) immediately
7.	↓	Descend to (FL) immediately
8.	RS	Right Side
9.	LS	Left Side
10.	→	Cruise
11.	— M →	Maintain
12.	X	Cross
13.	LT	Turn Left after Take Off
14.	RT	Turn Right after Take Off
15.	H-(NE)	Hold - (Direction from Fix)
16.	EAC	Expect Approach Clearance AT (Time)
17.	/\ or No DLA	No Delay Expected
18.	DLA INDFT (Time)	Delay Indefinite - Expect Approach Clearance Not Later Than (Time)
19.	UFA	Until Further Advised
20.	RL	Report Immediately on Leaving (Level)
21.	RR	Report Immediately on Reaching (Level)
22.	CE	Clearance Expires

(6) Direct Communication

Typical voice bandwidth is 3000 bits/sec.

(7) Command (G-A)/Command Request (A-G)

Command Data - G-A

	Bits
Time to Command - 0.62 hours	7
Command Heading - 352°	9
Command Heading to - Waypoint or Lat/Long	38
Command Altitude to - FL 46.2	10
ETA at - 22.42 hours	12
Hold at Waypoint - Waypoint or Lat/Long	38
Command Speed - 452 kts	10
Command Frequency - 119.2	13
Request Reply - Code	2
Req. Voice Contact at - Waypoint or Lat/Long	38
Time - 22,42	12

Data Words: 11; Bits: 184.

(8) Traffic Data (Advisory)

Requires: Teleprinter or CRT output.

	Bits
Target ID - UAL 2716	20
Range (A/C to Target) - 100.5 nmi	11
Bearing (A/C to Target) - 86.2°	9
Altitude - FL 46.2	10
Speed - S, F	2

Data Words: 5; Bits: 52.

3.6.2 Communication System Capacity

(1) Airborne

The capacity of the data link is analyzed in Appendix C. The results are summarized in Table XXIII. Shown are the Standard Report Data Requirements and the system capacity requirements, categorized per user aircraft. Although the clearance message utilizes a greater bit count than the standard report, the frequency of clearance changes is significantly lower than the frequency of linking a standard report. Recall that the standard report is the surveillance message in an ATC system that utilizes navigational data as the traffic control surveillance message. The standard report data therefore sizes the capacity requirement.

As shown in Table XXIII, the air carrier and GA3 bandwidth requirements approximate the 1200 bits/sec proposed, for near term usage, by air carriers and ARINC as the data link standard. The data link capacity shown in Table XXXIII is based on traffic forecasts in the 1980 time frame, i.e.:

Maximum density of A/C per hub in operations per hour

All air carrier and military and GA3: 50-372, Peak Hour

All GA: 611-4365, Peak Hour

Although GA1 and GA2 requirements exceed current data link bandwidth, VHF and UHF channels will accomodate the bit rate. However, communication and message content can decrease the system requirements. The interrogation rate strongly influences the data link bandwidth requirements. Trade-offs to decrease communication system capacity include:

(1) Code Set - arrivals, departures, ground traffic, enroute-low, enroute-high, altitude level

(2) Ground System Update - ground computation of aircraft position computed from the last surveillance report

(3) Compliance with the Flight Plan - per the Limit Logic concept which enables tighter flight plan tolerance

(4) Channel Allocation

(2) Ground Based

In an automated system employing navigation surveillance, ground storage data is required. Table XXIV shows the ground storage requirement is within the state of the art of large scale digital computers.

TABLE XXIII
STANDARD REPORT DATA REQUIREMENTS

	Option	Data Words	Bits	Capacity Bits/Sec Approach	Departure	Enroute-Low	Enroute-High
SST	1 2	11 11	165 155	10^3-10^4	10^3-10^4	10^3	10^3
GA3-CTOL-VTOL-STOL	1 2	11 11	162 152	10^3-10^4	10^3-10^4	10^3	10^3
GA1-GA2	1 2	11 11	145 122	4×10^3-10^5	4×10^3-10^5	4×10^3-10^5	-

TABLE XXIV
GROUND STORAGE REQUIREMENTS

Floating Point Ground Store	Air Carrier/GA3		GA1 - GA2	
	Low	High	Low	High
16 Bit Data Words	550	4,100	6,720	48,100
Total K Bits	91	675	970	7,000

SECTION 4

NAVIGATION TRAFFIC CONTROL SYSTEM RATIONALE

4.0 SUMMARY

This section presents the rationale of the advanced navigation traffic control system. It combines the statements of desired operational capability, navigation requirements, and communication requirements, presented in Section 3, into the concept of an advanced ATC system.

The advanced ATC system incorporates as system features those functions that are closely allied to present cockpit duties. It embodies a Flight Plan Reference Concept, a retrievable flight plan, a Limit Logic Concept, area navigation, and use of data link.

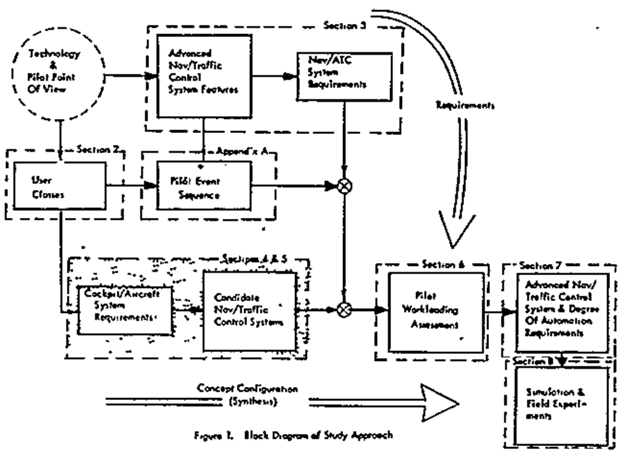


Figure 1. Block Diagram of Study Approach

The Flight Plan Reference is the heart of the advanced traffic control system. Flight plans are filed by both IFR and VFR users; however, controlled VFR operations occur only in controlled airspace. VFR flights in uncontrolled airspace need not comply. Therefore, in congested high density traffic airspace, the system establishes controllability over all users, giving practical flow control, hazard avoidance capability, and efficient utilization of an area navigation capability.

The flight plan is retrievable in both airborne and ground systems. The airborne system maintains cognizance of a stored flight plan. Simultaneously, the traffic unit monitors the progress of each flight with respect to the flight plan, and also the traffic flow. This procedure restricts the total volume of communications. It also curtails airborne and ground system communications by restricting these to surveillance interrogations and events which are keyed by exceeding Limit Logic conditions.

Limit Logic computations are those trivial airborne operations which check the aircraft progress with respect to an approved flight plan. The Limit Logic variables are increments in estimated time of arrival, deviations in altitude, deviations in assigned speed, cross track distance, and fuel remaining. When the limits are exceeded, the pilot is alerted and concurrently contact with the ground is initiated.

The format of the airborne system relies upon an area navigation system, a computer, and a data link. The onboard computer performs three functions: flight plan storage, Limit Logic comparison, and navigation and guidance computation. A code setting is provided in

the VHF transponder to acknowledge and respond to selective aircraft identification calls. The link between the air and the ground is closed when the aircraft overflies a mandatory waypoint, on interrogation from the ground (per code set), or when the Limit Logic in the ground system computation channels or airborne computation channels is exceeded.

The Flight Plan Reference system makes full use of the concept of area navigation. Waypoints, referenced to latitude longitude and coded for easy reference, define the start- and end-points of the departure, enroute, and approach paths. Waypoints also define reference points for holding patterns, traffic control vectors, and control points for the approach and landing phase.

Use of the Flight Plan Reference system requires that features of the ground system be postulated. Automated surveillance information drives the alphanumeric vertical situation data listing; the synthetic PPI horizontal situation display; and automated, flight data strips. The control format is the ETA technique, and flight filters serve to isolate aircraft not under a particular surveillance unit or control unit responsibility. Several ATC algorithms make extensive use of navigation surveillance data. Among these are: computer-aided approach sequencing, Limit Logic, position up-date, conflict prediction, radar and navigation data filtering, and general aviation position determination. Storage requirements encompass the current aircraft flight leg, the aircraft flight plan, met data, and NAVAID reference information. The included alternatives are NAVSAT ephemeris data, VORTAC identification and position, hyperbolic chain identification and lat/long, etc.

It is necessary that the interaction of this ATC system with each of the aircarrier and general aviation users be specifically outlined. The Flight Plan Reference, Event Sequence Diagrams do this. They are presented in Appendix A.

SECTION 4

NAVIGATION TRAFFIC CONTROL SYSTEM RATIONALE

The rationale of the advanced navigation traffic control system is derived from the combined statements of desired operational capability, and communication and navigation requirements discussed in Section 3 of this report. Fundamental to the successful implementation of this Advanced Navigation/Traffic Control System is the implementation of a system-mandatory Flight Plan Reference Concept. Under this concept flight plans are necessarily filed by all users of the system. All users will be expected to adhere strictly to an ATC-approved flight plan unless flying in uncontrolled airspace. The users of the system constitute all IFR and VFR flights operating in controlled airspace. Surveillance Data derived from the onboard area navigation system is to be linked via VHF data-link to the ground surveillance unit. To reduce the currently excessive amount of communications between aircraft and ground, the concept of Limit Logic is applied. The Limit Logic concept envisions the elimination of all communications unless the aircraft departs from its assigned flight plan by an amount greater than some number, e.g. delta, at which time both the pilot of the aircraft and the surveillance unit of ATC are appraised of this deviation.

4.1 DETAILS OF THE SYSTEM CONCEPT

Implementation of the Desired Operational Capability set forth in Section 3 of this Volume, will lead to development of the following system features:

(1) A Flight Plan Reference
(2) Active use of a Retrievable Flight Plan
(3) Broad use of Area Navigation
(4) Data Link
(5) Limit Logic

4.1.1 Flight Plan Reference

The Flight Plan Reference, the heart of the advanced traffic control system,

produces a number of needed effects. First, it ensures that the ATC system is advised of both the presence of an aircraft and the intentions of the pilot so that it can anticipate the possibility of a conflict and the need for an approach slot. Second, it imposes a discipline on the pilot in the form of a requirement to go where he has stated that he is going. Third, it provides the baseline for eventual implementation of Limit Logic and an automated output of surveillance information. Finally, it sets the stage for the use of a practical flow control and efficient utilization of an area navigation capability.

The proposed navigation traffic control system retains the organizational structure of the existing ATC system. The functions of surveillance, control and advisory services are the responsibility of both local and federal control personnel. They include Tower and Ground Control personnel who are responsible for the local service and Approach (Departure implied as well) Control and the Air Route Traffic Control Center personnel.

A natural and logical working relationship is maintained between the pilot and control personnel. ATC regulates the flow of traffic at the discretion of the controller, subject to pilot acknowledgement, and thereby attempts to achieve maximum use of the airspace. Control is augmented through implementation of IFR and VFR procedures. Surveillance functions require knowledge of aircraft present position, estimated future position with respect to time, and pilot intentions for all aircraft under control of the ATC surveillance unit. The control loop will be closed on VFR flights in controlled airspace through use of mandatory reports.

As has been stated, the control reference is the aircraft flight plan which is input to both the airborne and ground-based systems. The flight plan reference is extremely important in terms of establishing a workable control tool for the system. The pilot interfaces with ATC by maintaining aircraft flight path with respect to the approved flight plan, by complying with ATC commands regarding direction of flight (vectors), speed and altitude, by monitoring required communication channels, by setting required ident codes, and by complying with the clearance and/or amendments to clearance promulgated by the controller. The airborne derived surveillance information is data linked to the ground system upon demand or at specific reporting points, or is supplied by direct communications.

4.1.2 Retrievable Flight Plan

All user aircraft operating in controlled airspace would be required to file flight plans in the proposed system, regardless of whether the flight is to be VFR or IFR. The airborne system is to maintain continuous operational cognizance of the flight plan, while the traffic unit concurrently maintains a data file on each flight. This procedure restricts the volume of required cross-talk between the ground system and the airborne system to those occasions when a deviation is observed or when the ground system requires an update. There is no need for flight-plan-related communication unless certain limit conditions are exceeded.

4.1.3 Limit Logic

The Limit Logic is comprised of variables which describe aircraft progress with respect to an approved flight plan. When these variables are exceeded, the pilot is alerted and concurrently contact with the ground is initiated. The Limit Logic variables are increments in Estimated Time of Arrival (ETA), error in altitude, deviations in assigned speed or cross track distance and/or fuel remaining. These variables correspond to standard flight plan status checks. The degree to which the concept is automated depends upon the onboard avionics fit.

Testing of the Limit Logic should be performed automatically in a secure system. However, the cost of such a system might preclude its use by GA 1, in which case the check would be made by the pilot. The degree of automation will depend upon the nature of the area navigation system installed in the aircraft.

4.2 SYSTEM BENEFITS

The system concept is designed to promote schedule reliability, efficiency of operation, economy of operation, and to minimize workload without compromise to present level of safety. In addition, it has the following desirable characteristics:

(1) It will permit pilots of all qualifications access to controlled,

congested airspace. By instrumenting aircraft with understandable, easy to operate navigation and communication equipments which are compatible with the ATC control and surveillance units, restrictions against use of densely populated airspace will diminish.

(2) It will minimize pilot workload related to navigation and communication management by reducing the total number and frequency of required communications.

(3) It will coordinate the navigation management and hazard avoidance tasks which a pilot normally performs and will increase the level of protection from hazards to flight through ground storage of all flight plans, thereby presenting the possibility of generating an early warning of the close approach to an obstacle or other hazard.

(4) It will complete the control loop between the ATC system and <u>all users</u> of the airspace, offload the surveillance data acquisition task faced by ATC, and provide ground control with the potential for continuous surveillance information.

(5) It will place responsibility and authority for navigation back into the cockpit, yet will meet the 1975 - 1985 navigation and communication requirements while retaining the same ATC functional structure now in being.

From the pilot's point of view the system supplies positive control of information

and communication information; can be designed to provide anticipation of flight plan changes; provides flexibility in route structure and permits the pilot to retain responsibility for navigation of his own flight even when operating in congested airspace.

4.3 FORMAT OF THE AIRBORNE SYSTEM

The airborne system is comprised of the navigation and guidance system and the communications system. Organization of the airborne system is shown in Figure 18. Depending upon category of user, the onboard computer performs three functions:

(1) Flight plan storage
(2) Limit Logic comparison
(3) Navigation and guidance computations

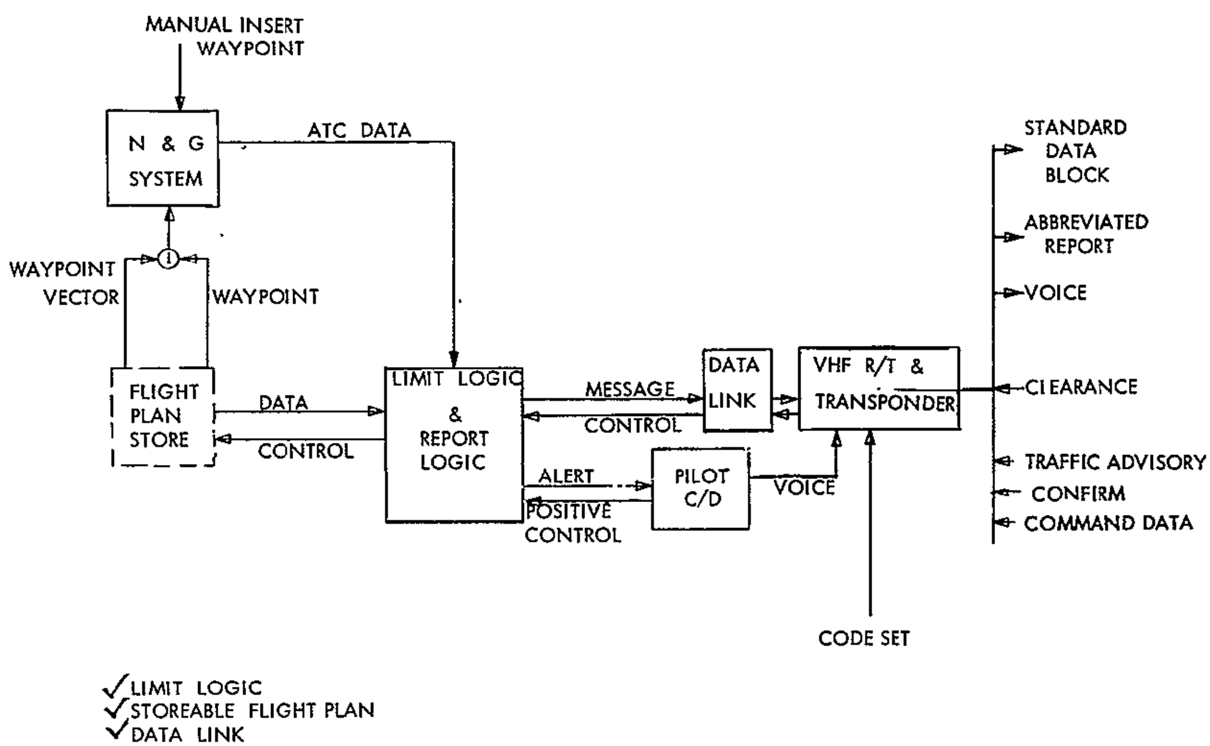


Figure 18. Format of the Airborne System

For GA 1, GA 2 aircraft the flight plan storage unit would be either a low cost special purpose computer or the pilot's flight plan and chart. The Limit Logic rationale therefore might be the equivalent of today's IFR procedure wherein the pilot is obligated to stay within a certain operating envelope and to advise the ATC system anytime he deviates therefrom. In an airborne computerized system, the three functions would be performed automatically. The latter approach is virtually mandatory if a sanitary system is to be devised.

The required ATC-related surveillance data is output from the Navigation and Guidance computer and compared with the stored flight plan data. If the system is within the specified tolerance, the Limit Logic will not be exceeded and only conventional flight path management data will be displayed to the pilot. The flight will continue along its assigned track until the system cycles onto the next leg in the flight plan. If the Limit Logic is exceeded, the pilot is alerted and subsequently takes whatever corrective action is required to return to the assigned flight path. The same alert signal is sent to ATC and triggers a validation check or status report.

The flow diagram in Figure 18 shows provision for a manual insert of waypoints to the navigation system, should an instruction be received by voice link. The system is designed to accept a temporary or permanent change of waypoint upon command from either the voice or the data link. The vector waypoint insert may be in the form of a change to an enroute waypoint, to a terminal area waypoint or to landing waypoint. Positive control is maintained throughout the flight. The data are linked to the ground unit when the Limit Logic is exceeded, or when a mandatory report point is overflown, or when the system is interrogated by the ground unit.

Figure 19 shows the detailed format of the airborne system. The system should be automated, but could be retained as a manual operation for general aviation (GA 1, GA 2). The Limit Logic, flight plan store, and area navigation system operate as follows. Assume that the aircraft is operating in accordance with the nominal flight plan which is stored both in the airborne and ground based systems. The complete flight plan which utilizes approximately 22 data words supplies current situation information such as TAS, GMT, command altitude, etc. to the Limit Logic. The destination or waypoint code, for example, Melrose, Junes, Colts Neck, is inserted into the navigation system.

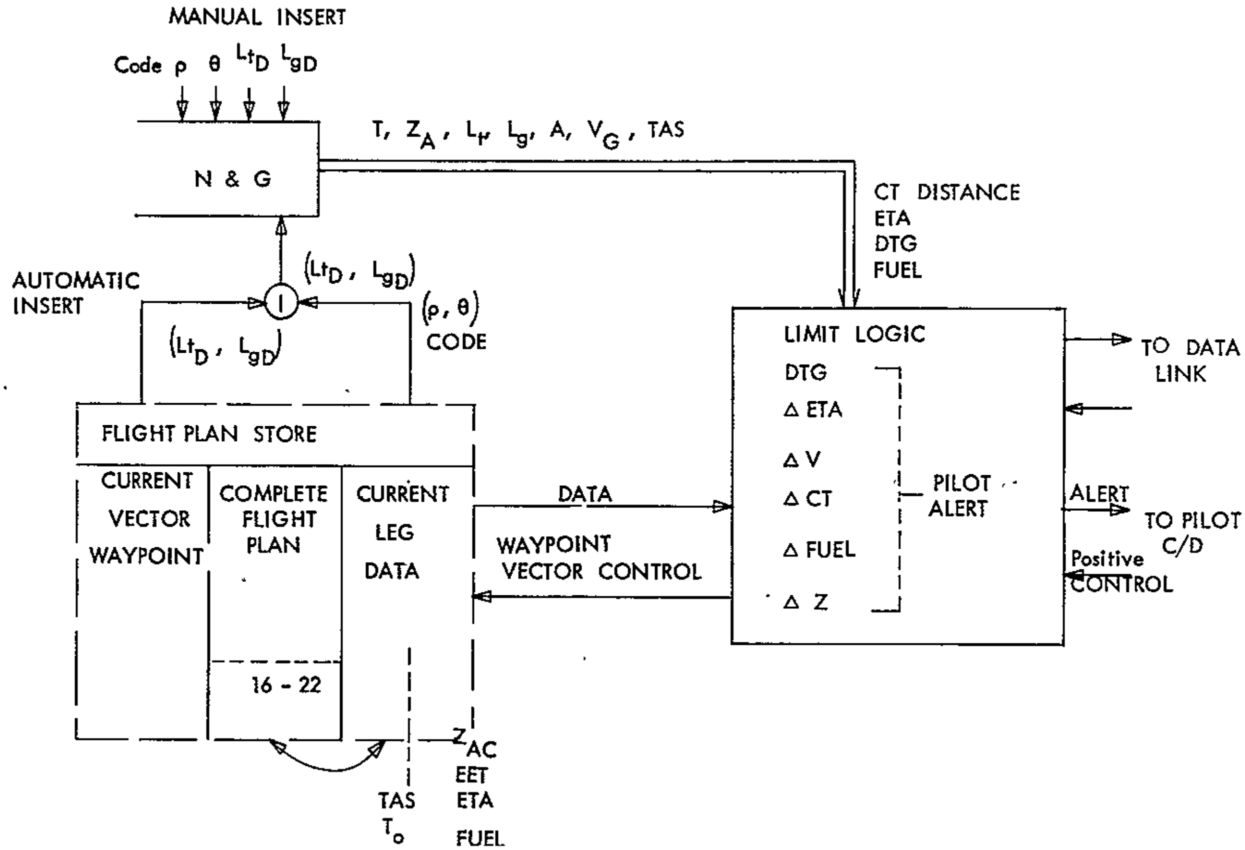


Figure 19. Airborne NAV ATC Reference

The standard report data block and system status are compared for tolerance acceptability by the Limit Logic. Whenever the significant variables are out of tolerance with respect to the approved flight plan the pilot is alerted through the control display panel. The message of the standard data block is data-linked to the cognizant ATC surveillance unit. Alternatively, when the distance to go (DTG) to a mandatory fix point is nulled, a report is automatically transmitted to the ground. Since currrent flight plan data is stored and available for display on the ground, an abbreviated single data word can be linked to the ATC surveillance unit in the form Aircraft Ident, Time and DTG = 0. Voice communication can be used upon request.

The system is designed to allow ATC to institute flow control in order to relieve congestion in the terminal area through automatic insertion into the airborne system of vector waypoints. The term 'Vector Waypoint' is used throughout this study to indicate an arbitrary

place, not necessarily located at a radio facility or published intersection, selected by ATC as a means of instituting a path stretching procedure.

The four fundamental system components are the -

(1) Limit Logic

(2) storable flight plan

(3) data link

(4) navigation and guidance computer

Figure 19 shows the communication, control and advisory interface with ATC. There is a code setting provided in the VHF transponder to acknowledge and respond to:

(1) A/C selective identification calls

(2) A/C destination terminal

(3) response to ATC control, surveillance, and advisory unit

The pilot is notified that the aircraft has reached the turning point or end of leg by the Limit Logic subroutine. At that time the system extracts information for the upcoming leg, e.g. coordinates of next waypoint, required altitude and speed, required time of arrival, etc. and calculates therefrom steering error and ETA. Provision is made to accomplish leg changeover either automatically or manually.

The navigation and guidance (N and G) computer receives waypoint information in 3 ways:

(1) from the flight plan (leg set can be accomplished either by manual or automatic means).

(2) by manual insert (coordinates or coded)

(3) by vector waypoint insertion initiated by ATC.

It has been stated that precisely defined parallel and slant tracks will be required in the 1975 - 1985 system. This capability will require a fully automated 3-dimensional system with the capability to receive inputs of altitude or flight level information in conjunction with specified waypoints. The aircraft Automatic Flight Control System (AFCS) then drives the aircraft along the slant track. The N and G computer outputs navigation management data to the Limit Logic system. This data includes a standard report format which includes ETA,

distance to go, fuel remaining, cross track distance, ground speed and altitude.

The Limit Logic function compares actual progress with expected progress. If any of the critical deltas are exceeded, e.g. ΔETA, Δspeed, Δcross track distances, Δfuel, or Δaltitude limits, the pilot is alerted and an aircraft report is data-linked to the ground. The limits on ETA, speed, cross track, fuel or altitude are set separately for the accuracy requirements in terminal area and enroute flight phases. If no deviation occurs it is assumed that the flight path is maintained within bounds, and no report is issued or requested.

The Limit Logic computation is also performed in the ground system. It is necessary that the ground system maintain this tracking and computational function because: (1) ground position update reduces communications, and (2) in a system which uses non-fixed ground signal reference points (i.e. VOR), an error can be made in the manual waypoint selection.

The link between the air and the ground is closed:

(1) when mandatory waypoint, enroute, terminal area or land point is overflown;

(2) on interrogation from the ground;

(3) when Limit Logic in the ground system computation channels or in the airborne computation channels is exceeded.

Other specific points at which reporting occurs are outlined in the Event Sequence Diagrams in Appendix A.

Generally, unless the pilot is directed to omit them, he operates the system so that reports are issued whenever the following points are intersected: scheduled waypoints, vector waypoints, holding pattern fix points, the "low station" or final approach fix, and the outer and inner markers during final approach. The landing waypoints are different for each particular user, GA 1, CTOL, VTOL, STOL, etc. It is visualized that a mandatory report point would be signified through encoding of the waypoint. When the point is over-

flown a signal is initiated which will transfer the standard or abbreviated report to the ground

The remaining communication functions and message content are discussed in Section 3.3 and 5.6. Note that:

Command Data is a two-way function; down-link corresponds to a request for clearance or amendment thereto, while up-link corresponds to the clearance or instructions to change direction, speed or altitude.

Confirmatory Message is also a two-way function; content of this message includes acknowledgement, identification, or request for voice communication.

Code Set function minimizes data rates and the possibility of saturation of the system. Codes that can be set could include: aircraft identification; destination airfield or VTOL-pad.

Figure 20 shows the A-G surveillance information flow; Figure 21 shows the G-A control information flow. This system format is reflected in the Event Sequence diagrams shown in Appendix A.

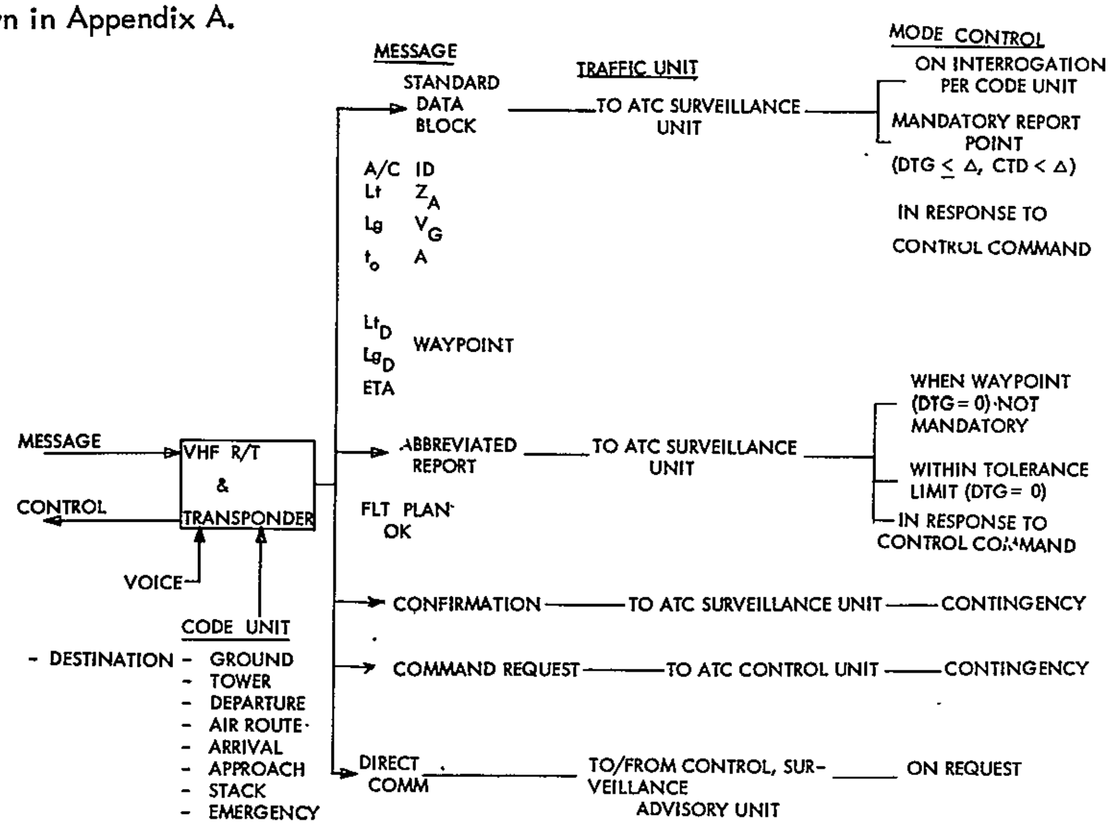
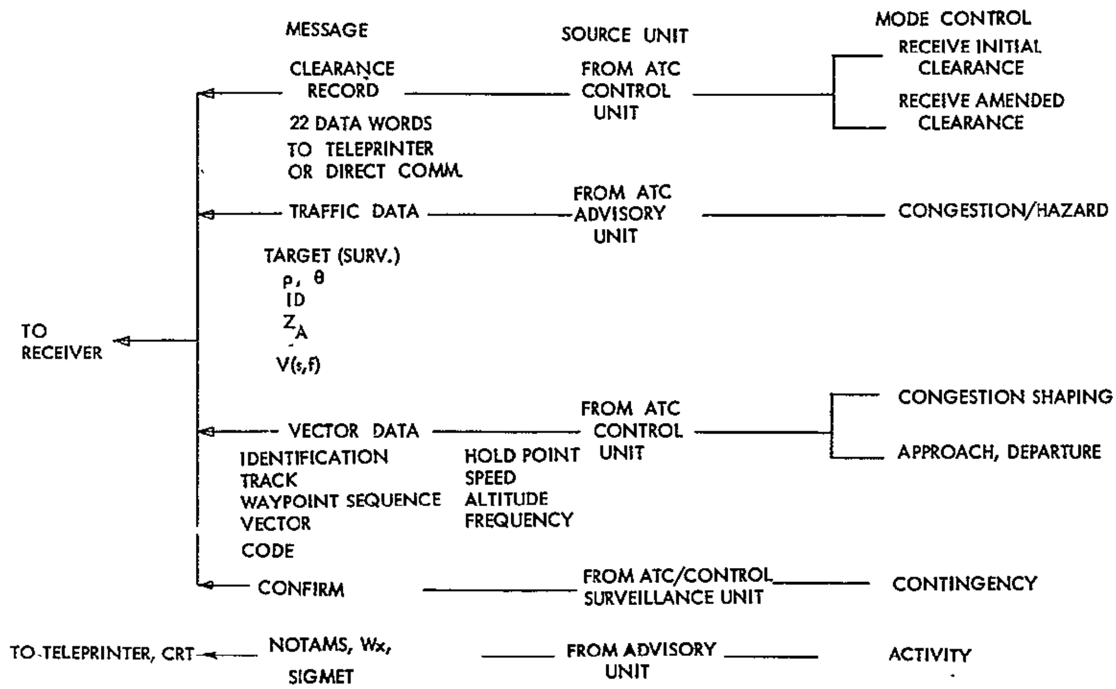


Figure 20. Surveillance Information Flow (A-G)



4.4 AREA NAVIGATION

The Flight Plan Reference system makes full utilization of the concept of area navigation. Waypoints are related to latitude and longitude rather than to the present rho/theta VHF radio navigation system and are used to define the start and end points of the departure, enroute and approach paths. Waypoints also define reference points for holding patterns, traffic control vectors, and control points for the approach and landing phase.

The following sub-sections describe the use of the Flight Plan Reference system and area navigation concept as a navigational aid.

4.4.1 Terminal Area Departure, Including Vectoring

Figure 22 illustrates the terminal area departure flight phase showing departure tracks for four classes of aircraft - VTOL and STOL, SST, or CTOL jet. The flexibility of the system is indicated by the two tracks defined by separate sets of waypoints.

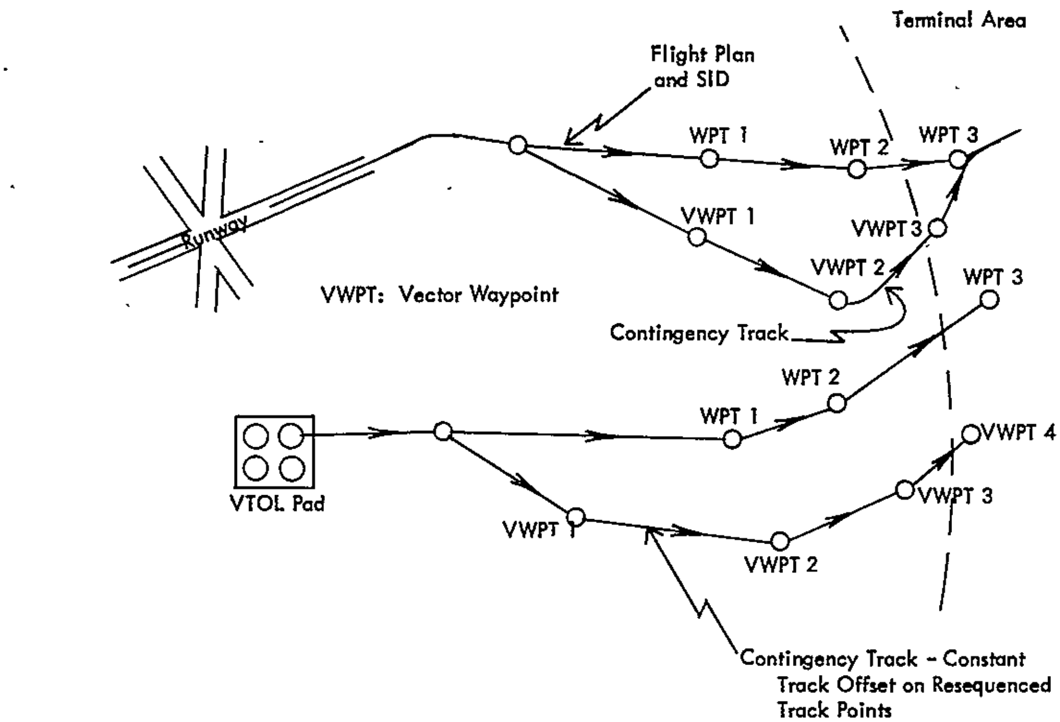


Figure 22. Terminal Area Departure, Including Vectoring

Prior to departure, waypoints and required flight levels or altitudes corresponding to the Standard Instrument Departure (SID) are inserted into the airborne system as WPT 1, 2, 3 . . . . During flight in the terminal area the VTOL aircraft attempts to maintain assigned track within Limit Logic. Should the tactical situation require a change in flight plan, vector waypoints are inserted into the airborne system. These vector waypoints VWPT 1, VWPT 2, VWPT 3, are designed to override the original set of waypoints, e.g. WPT 1, WPT 2, WPT 3. With the approval of the pilot, and at the command of Departure Control, the revised flight plan is followed.

The VTOL track illustrates the capability of the system to employ parallel or offset tracks to handle contigency situations.

The departure phase transitions directly into the enroute phase. Wherever possible the flight will conform as closely as possible with the direct path.

4.4.2 Enroute or Terminal Area Hold

Figure 23 illustrates a constant altitude holding procedure. WPT 5, WPT 6, and WPT 7 are used to define the original track sequence. Between WPT 5 and WPT 6, ATC requests that the aircraft use H1 and H2, holding waypoints at a fixed track offset. These are inserted into the system. Air route surveillance unit hands off the flight to the hold surveillance unit. The AFCS is programmed for H1, H2 and hold offset. The second data insertion upon receipt of clearance to depart the hold pattern, is to insert H1, H3, and WPT 7 as the amended flight plan, revising WPT 5, WPT 6, WPT 7.

Figure 24 illustrates an area navigation holding pattern utilizing a conventional DME or DTG hold technique.

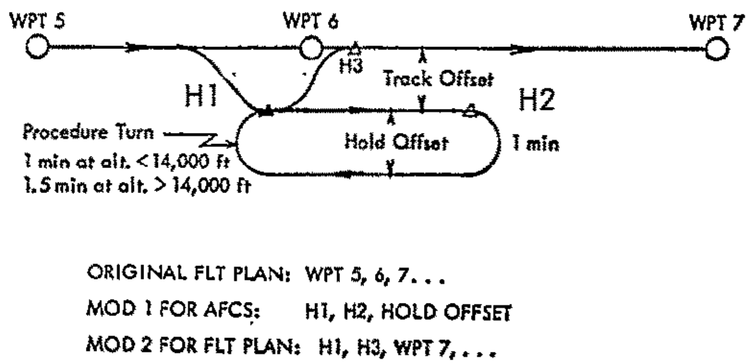


Figure 23. Enroute or Terminal Area Hold

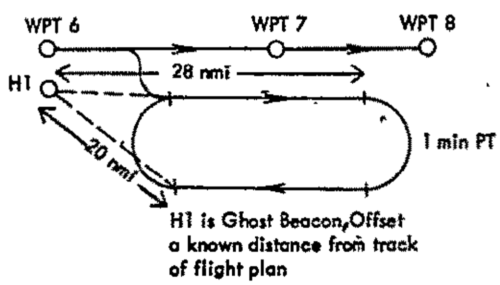


Figure 24. Holding Pattern with DME or DTG

4.4.3 Descent to the Terminal Area

Figure 25 illustrates STOL and VTOL aircraft descent to the terminal area. Scheduled descent is initiated between WPT 7 and WPT 8. However, prior to terminal area entrance, if a contingency communication occurs, a track offset could be used to delay the aircraft. The vector waypoints VWPT 1, VWPT 2, replace WPT 7 and WPT 8. The Flight Plan Reference concept is revised accordingly to fit with WPT 9. WPT 9 is a conventional Intercept Point (IP).

The VTOL orientation shows the location of Final Approach Waypoints – LN 1, LN 2 and LN 3. Prior to approach and landing, a contingency communication could command a terminal area hold.

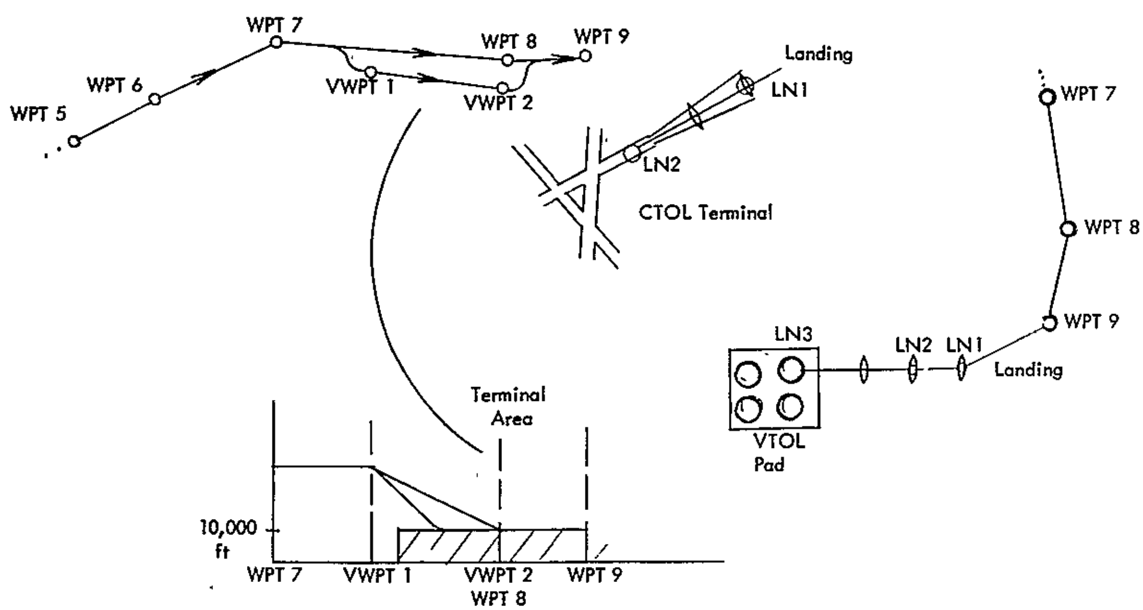


Figure 25. Enroute Descent to Terminal Area

4.4.4 Terminal Area Hold

Figure 26 illustrates the terminal area hold pattern. The programmed waypoints in the original flight plan are WT 7, WPT 8, and WPT 9. The original flight plan utilizes area navigation to complete the STOL landing through the use of WPT 9, LN 1 and LN2. The modification to the programmed flight waypoints uses two inserts to the Automatic Flight Control System (AFCS). The horizontal system uses hold points H1, H2 and the hold offset mode. The vertical profile system complies with H1, HV 1, and a fixed descent rate. Upon clearance from the pattern, H2, V1, LN 1, and LN 2 are sequenced into the system. The land points (LN) 1, LN 1 and LN 2, are inserted as standard, never changing coded points. These points are associated with identifiable features, such as air terminals which constitute specific VTOL pads.

4.4.5 Area Navigation Approach

Figure 27 illustrates the differential-time-difference and time-difference approaches. The VTOL scheduled profile maintained in the Flight Plan Reference storage is defined by WPT 5 ... WPT 9. Terminating the enroute cruise phase at WPT 5, the VTOL departs the route structure to begin the programmed descent through WPT 6 and WPT 7

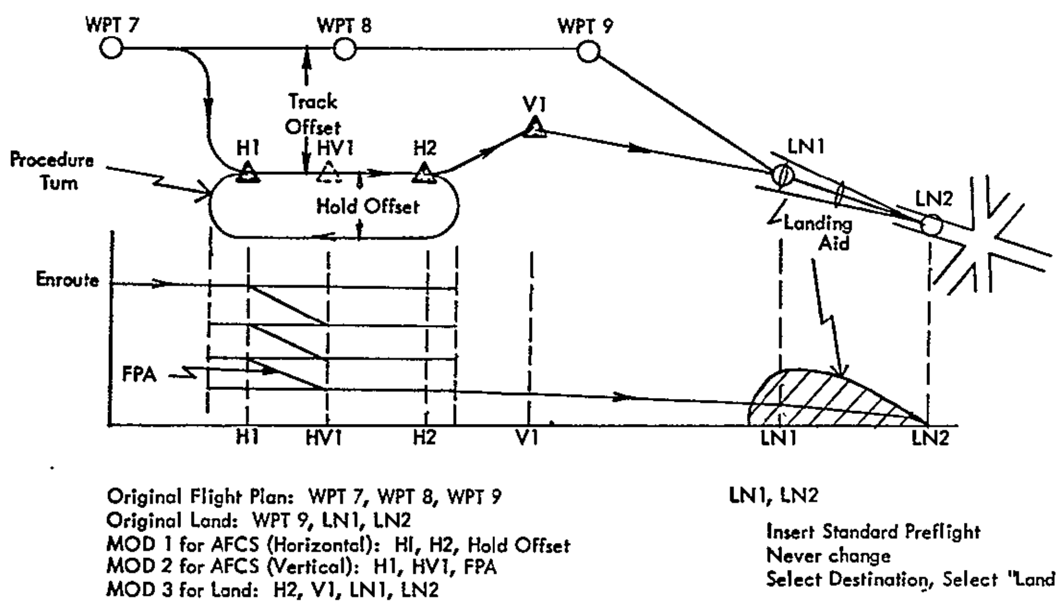


Figure 26. Terminal Area Approach Hold

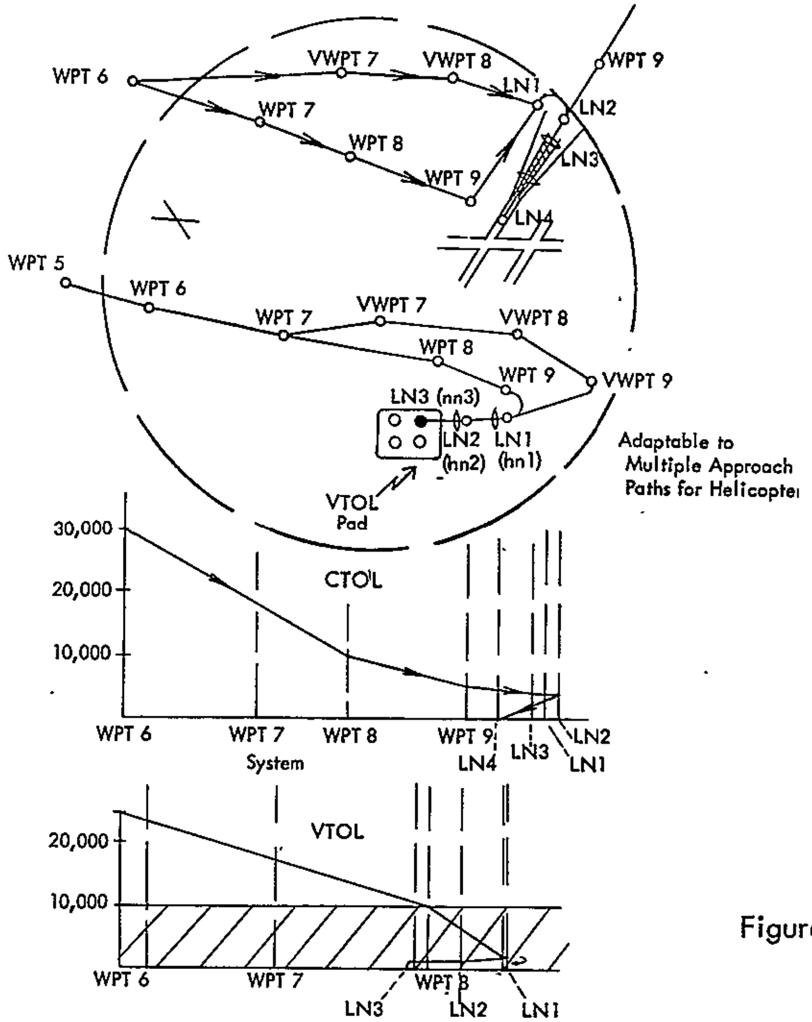
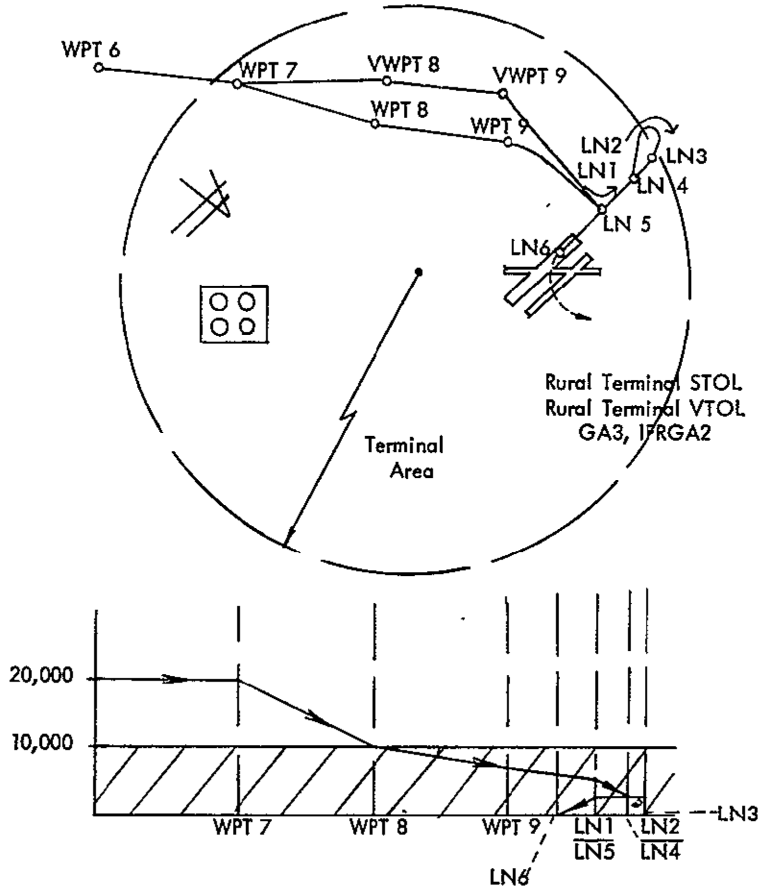


Figure 27. Area Navigation with a DTD Approach or a TD Approach

to the terminal area. Prior to the intersection of WPT 8, the differential calibration signal is inserted into the system. As the approach control unit maintains surveillance, programmed descent continues through WPT 9. The differential signal is updated and approach is completed through LN 1 ... LN 2, to the landing at LN 3.

Should contingency communications develop in the terminal area, the air route control unit links the vector waypoints to the system. Should schedules change, approach control would change the vector waypoints or initiate conventional vectoring. VWPT 7, VWPT 8 and VWPT 9 illustrate flow shaping and path stretching to accomodate increased traffic. Also, multiple approach paths are available.

Figure 28 illustrates the use of area navigation and the Flight Plan Reference system in completing a VOR approach. Although this landing procedure is used with ILS



Note: Above configuration is typical also of an ILS Approach.

Figure 28. Area Navigation with a VOR Approach

facilities and rural area air terminals without ILS facilities, this technique is not evaluated in Appendix A, chiefly because it is a capacity limiting procedure. Full use of the area navigation system would permit proper alignment to the desired runway and reduce pilot workload in the approach.

Replacing the VOR approach with the area navigation system eliminates limited access caused by the VOR approach. Limitation in the number of users on the path is caused by inaccuracy in the aircraft track during the outbound leg; also by drift due to wind during the procedure turn. The area navigation, surveillance link system assures aircraft track keeping and continuous surveillance data for ATC.

4.5 FORMAT OF THE GROUND SYSTEM

For the purpose of completeness, a ground system is postulated which could complement the automation of the airborne area navigation and Flight Plan Reference System, and take full advantage of the navigation data to upgrade service completeness. Figure 29 shows how surveillance and control information flow of the ground system complements the airborne system. Figure 30 shows the functional flow diagram of the ground computations and storage. The flow diagrams represent only the format of the signal flow, and therefore consolidate all traffic control, surveillance, and advisory units -- terminal area, enroute, tower, etc.

4.5.1 Surveillance and Control Information Flow

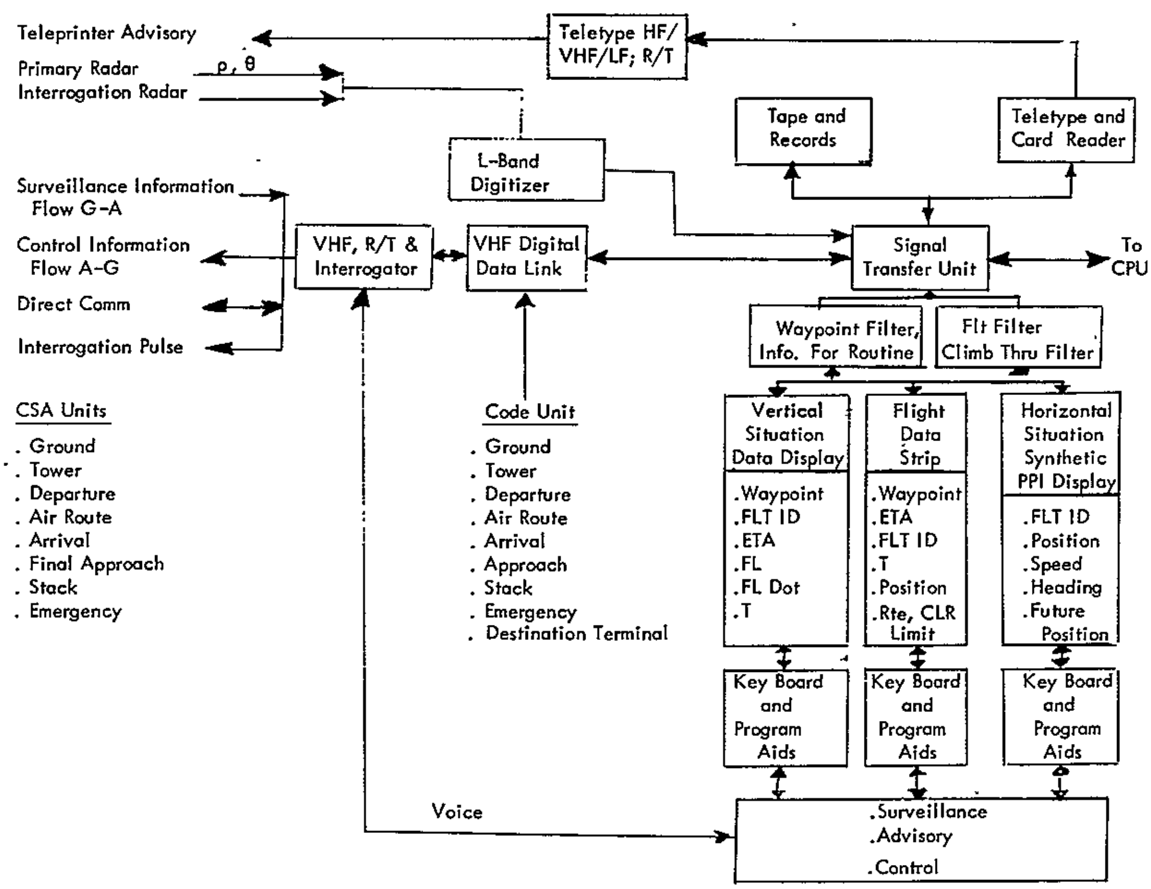


Figure 29. Ground System Surveillance and Control Information Flow

Figure 30 illustrates the interface between the data link and the ground system control, surveillance, and advisory functions. Automated surveillance information drives the vertical situation display, the horizontal situation display, and automated flight data strips. The vertical situation display is an alphanumeric data listing; the horizontal situation display is a computer-driven synthetic PPI display; the flight data strips are automated. The control format is the ETA technique. Increasing aircraft densities requires the use of flight filters. The filters isolate those aircraft not under the surveillance or control unit's responsibility. For example, particular waypoints could be filtered per each VSD and altitude sectorization on the HSD.

The G-A and A-G link is shown as a VHF digital data link set to the appropriate code setting. Keyboard and program aids such as cursor markers, a light pencil, or electro-screen permit the operator to interface with the specific aircraft in the system; to call data on that aircraft; and to modify flight plans in accordance with

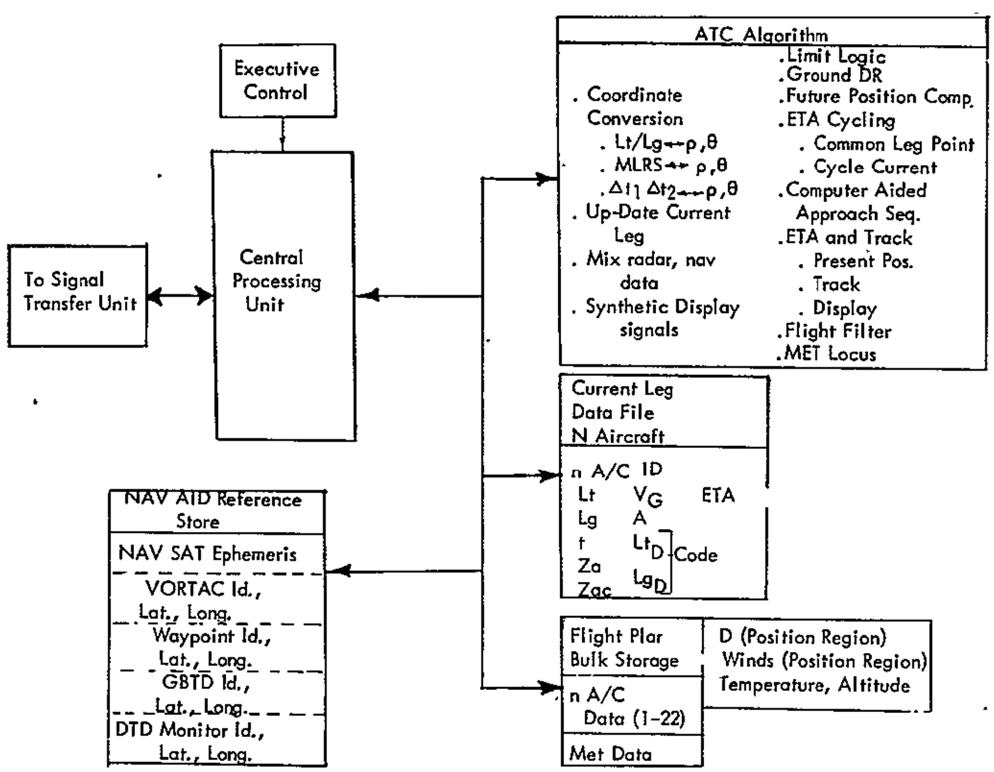


Figure 30. Ground Computations and Storage

the Flight Plan Reference system.

The teletype selectively links advisory data to the air carrier user.

4.5.2 Ground Computations and Storage

A minimum Flight Plan Reference System would incorporate the features shown in the flow diagram of Figure 30.

ATC algorithms include coordinate conversions of lat/long to range and bearing, coded waypoints to range and bearing, time difference values (low class GA users) to range and bearing. The navigation system reported surveillance data, converted to range and bearing, is mixed with the radar surveillance data and conditioned for presentation on the synthetic computer driven displays. In addition to present position, forecast position based on ground dead reckoning is output to the display panel. The Limit Logic is then checked. Other algorithms include computer aided approach sequencing, ETA cycling to check conflict conditions on current Flight Plan Reference Legs, and generation and synthetic display of present position and aircraft track. The flight filter algorithm would sectionalize all aircraft data as needed, e.g., per track, sector, altitude sector, climb through or descending aircraft. The Met algorithm defines regions of winds and turbulence, and restricts flight commands into restricted regions.

The data file stores the current aircraft flight leg and the information for computation of ground-based Limit Logic and ground dead reckoning. The data of the current leg is continually cycled through the ETA control to determine if the Limit Logic is exceeded.

Other storage requirements include complete flight plans and access to Met data. The NAV AID Reference Store designates access to any of the following: NAV SAT ephemeris data, VORTAC identification and lat/long, coded waypoint identification and lat/long, hyperbolic chain identification and lat/long, and differential time difference and lat/long. The data is used in position-fixing computations.

SECTION 5

AREA NAVIGATION SYSTEMS

5.0 SUMMARY

One objective of the NAVTRACS program was to recommend automation requirements of an advanced ATC system that utilizes an area navigation system. The automation requirements are based on minimizing pilot and copilot workload in the performance of their cockpit duties. However, prior to undertaking the workload/automation tradeoff analysis, condidate navigation systems must be selected--feasible systems for use as an area navigation aid. This section compares the ATC operational requirement of Section 3 with the capability of a number of candidate navigation systems. It evaluates their characteristics and determines whether the systems can meet the area navigation, approach, and landing system requirements.

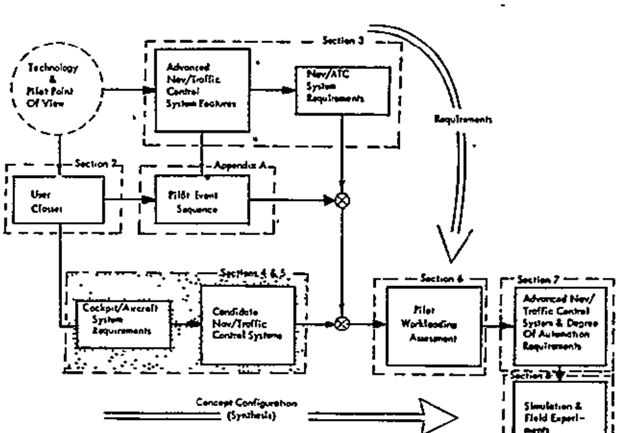


Figure 1. Block Diagram of Study Approach

Area navigation system evaluation is based on two requirements. Qualitative evaluation is based on the navigation aid operational requirement. Quantitative evaluation is based on the navigation aid accuracy requirement. Of twelve system configurations studied, three systems--navigational satellite, LF/CW and LF/pulsed ground based time difference--completely satisfy the area navigation performance requirement. The rho-theta system, and also the precision rho-theta system, when equipped for area navigation with a course line computer meet the operational navaid requirement. However, not all systems meet the navaid accuracy requirement.

The acceptability of each navaid, with respect to required precision, depends on the user and flight phase. A navigation accuracy requirement of 0.5 nmi (3σ) exists for all user aircraft operating in enroute, congested airspace and terminal areas. It can be attained utilizing rho-theta, NAVSAT, and GBTD systems. The 0.3 nmi (3σ) accuracy requirement for climb, descent, and approach navigation is set for general aviation users and can be achieved using precision rho-theta, NAVSAT, and GBTD. The required area navigation accuracy for establishing a holding pattern is 0.12 nmi (3σ). Precision approach accuracy for the aircarrier user is 360 ft. Although precision rho-theta and GBTD systems can meet the holding pattern requirements marginally, the precision approach requirement can only be met with the NAVSAT system. GBTD can not comply. However, a GBTD system can be modified in order to reduce the system errors to an acceptable level. Differential GBTD techniques achieve this effect. Differential NAVSAT and differential GBTD, when integrated with accurate velocity information, can also provide a CAT-II(a) landing capability.

Based on the 1975-1985 operational requirement, GBTD (LF/CW, LF Pulsed), precision rho-theta, and NAVSAT systems are acceptable navigation aids for enroute, climb out, descent, and terminal area flight. As approach aids, NAVSAT, differential NAVSAT, differential LF/CW, and differential pulsed systems are candidates. The candidate systems are evaluated, therefore, in Section 6--in varied communication, navigation, and identification systems. The systems are tied to the Flight Plan Reference, traffic control concept.

Because of marginal acceptability, and the need for a base line system, a rho-theta system is also evaluated. It is configured as an area navigation system.

SECTION 5

AREA NAVIGATION SYSTEMS

This section summarizes the capability of a number of candidate navigation systems to meet the area navigation, approach and landing systems requirements detailed in the preceding section, with emphasis on expanded area navigation. VOR/DME, PVOR/PDME, with and without course line computer, NAV SAT, GBTD (VLF-CW, LF-Pulsed, LF-CW), Differential NAV SAT, Differential GBTD and hybrid radio-inertial systems are evaluated with emphasis placed on three candidates: LF-Pulsed, LF-CW and NAV SAT.

Because of the study's emphasis on evolving a system which recognizes the point of view of the pilot, the effect on pilot workload (discussed in detail in Section 6) is used as the principal measure of acceptability of each area navigation candidate. In addition to meeting accuracy and availability criteria, a candidate judged to be acceptable had also to be capable of supplying required surveillance data to the data link subsystem and all navigation-related command and situation information required by the pilot at minimum increase to the nominal level of work. Pilot workload is strongly dependent upon onboard automation - the integration of the receivers, area navigation systems, computers, data link and display. Section 6 presents the system levels of automation. This section summarizes the basic capability of area navigation systems.

5.1 SYSTEM REQUIREMENTS

Section 3 explained the factors which established the baseline navigation and communication requirements used in this study and operational capability desired of the ATC system. These requirements are summarized in Tables XXV through XXVIII. The values of required accuracy of position appearing in Table XXVIII are 3σ values. This minimum horizontal accuracy requirement has been derived from an assessment of the 1975 to 1985 aircraft movements data provided as an input to this study. A second premise adopted in deriving the accuracy requirements is that virtually all airspace is controlled,

TABLE XXV
GENERAL NAVIGATION OPERATIONAL REQUIREMENT

Non-saturable for Users	Minimal Number of Ground Stations
LOS Independent	All-Weather (IMC)
Flexible to ATC Route Structure/Vectoring	Real Time Operation
Avoid Frequency Saturation	Growth Oriented
Area Coverage	Flight Path Adaptive
Time Independent	Generate ATC Surveillance Data
Map Reference	Compatible with Onboard Subsystems and Pilot Information Needs
Common Output Format	Satisfy Accuracy Constraint
Fail Operational	Minimum Pilot Workloading

TABLE XXVI
ATC-RELATED NAVIGATION FUNCTIONS

Commonality and Ground Use of Data

Interface to ATC Surveillance Unit

Respond to Traffic Control Unit

Provide Holding Capacity

Provide Slant Tracks

Provide for Waypoint Vectoring

Automatic Reporting

Supplement Radar Surveillance Data per Flight Phase

Tactical Flight Control

Note: Tables XIII and XIV have been repeated here for easier reference.

TABLE XXVII
INFORMATION NEED SUMMARY - NAVIGATION FUNCTIONS

Navigation Management Function	Flight Phase		Pilot Information Need Derived from Input	Input
	Terminal	Enroute		
Review Met Forecast	X	X	wind along track component wind cross track component	G-A comm. - wind direction, wind speed, temperature, pressure, visibility
Review Current Track	X	X	desired track distance to go	ground facility - range, bearing, mag heading, flight plan
			desired track distance to go	waypoint (wpt.) - wpt. lat., wpt. long, aircraft lat., aircraft long., mag. heading, flight plan
Update Steering	X	X	track angle error	traffic control vector - drift angle, mag. heading
			track angle error	flight plan track - range, bearing to facility, drift angle, mag. heading
			track angle error	flight plan track - wpt. lat., wpt. long., aircraft lat., aircraft long., drift angle, mag. heading
Flight Path Status Check	X	X	cross track distance ground speed estimated time of arrival altitude rate altitude	elapsed time, true airspeed, along track wind, mag. heading, drift, distance to go, pressure altitude, desired track
Flight Plan Status Check	X	X	distance to go cross track distance estimated time of arrival ground speed altitude fuel remaining	flight plan, throttle setting, pressure, density, airspeed, wind along track, elapsed time, fuel capacity

TABLE XXVIII
SUMMARY - MINIMUM HORIZONTAL ACCURACY REQUIREMENT IN CONTROLLED AIRSPACE, 1975-1985

AIRCRAFT / FLIGHT PHASE	IFR AND VFR					VFR FLIGHT PLAN REFERENCE	
	SST	CTOL JET	VTOL	STOL	GA3	GA2	GA1
TAXI	35 ft	35 ft	15 ft	25 ft	35 ft	NA	NA
TAKE-OFF	35 ft	35 ft	15 ft	25 ft	35 ft	NA	NA
CLIMB-OUT	0.5 nmi	0.5 nmi	0.5 nmi	0.5 nmi	0.5 nmi	0.3 nmi	0.3 nmi
ENROUTE - LOW	0.5 nmi	0.5 nmi	0.5 nmi	0.5 nmi	0.5 nmi	0.5 nmi	0.5 nmi
ENROUTE - HIGH	1.6 nmi	0.5 nmi	0.5 nmi	0.5 nmi	0.5 nmi	NA	NA
ARRIVAL	0.5 nmi	0.5 nmi	0.5 nmi	0.5 nmi	0.5 nmi	0.5 nmi	0.5 nmi
DESCENT	0.5 nmi	0.5 nmi	0.5 nmi	0.5 nmi	0.5 nmi	0.3 nmi	0.3 nmi
APPROACH	360 ft	360 ft	360 ft	360 ft	360 ft	0.3 nmi	0.3 nmi
LAND - CAT II	75 ft	75 ft	25 ft	50 ft	75 ft	NA	NA
LAND - CAT IIIC	15 ft	15 ft	15 ft	15 ft	15 ft	NA	NA
TAXI	35 ft	35 ft	15 ft	25 ft	35 ft	NA	NA
HOLDING	0.12 nmi	0.12 nmi	0.12 nmi	0.12 nmi	0.12 nmi	0.12 nmi	0.12 nmi

* Note: Tables XVI and XVII have been repeated here for easier reference.

even for VFR flights.

5.2 CANDIDATE SYSTEM EVALUATION

Eight basic navigation systems were considered to be candidates for use in the 1975-1985 time frame. Before their elimination through evaluation, the initial list of candidates included:

Rho-Theta:

- VOR/DME
- VOR/DME with Course Line Computer
- PVOR/PDME
- PVOR/PDME with Course Line Computer

Time Difference:

- NAV SAT
- VLF-CW (Omega)
- LF-Pulsed (Loran)
- LF-CW (Decca)

(VLF-CW, LF-Pulsed, LF-CW: Ground Based Time Difference (GBTD) Systems)

All of the Time Difference systems are assumed to accept a calibration signal, called differential time differencing, for use in selected terminal areas. This capability expands the systems to be evaluated to a total of twelve.

The ground based navigation aids must be augmented with a dead reckoning system - air data, doppler or inertial - to ensure the continuous availability of ATC-required surveillance data and pilot- (or autopilot-) required steering, speed and altitude data.

The evaluation shows that NAV SAT, LF GBTD, and PVOR/PDME employed in area navigation configuration are all adequate and feasible system concepts. Each of these acceptable systems is evaluated at different levels of automation to determine its suitability in the sense of pilot workload. Results are reported in Section 6.

Because the navigation accuracy requirement during the approach and landing phase is more demanding for VTOL and STOL than for CTOL aircraft, differential-NAV SAT and differential GBTD concepts are suggested.

The VTOL aircraft approach system is designed around a time difference receiver, a differential time difference update, radar altimeter, and dead-reckoning subsystem. Progress along the approach path is confirmed through use of Marker Beacons. The VTOL navigation system receives redundant position update from a PDME installed at the landing pad. A forward-looking obstacle avoidance radar supplies the pilot with hazard warning information and confirmation of the location and status of the landing pad. Air-carrier VTOL aircraft are assumed to employ an inertial system dead-reckoning aid. Altitude calibration is achieved through use of a radar altimeter, perhaps updated at the Marker Beacon. (Section 6.3 outlines the system concept.)

In this analysis it was assumed that the STOL aircraft was equipped with a system which would accept a differential time difference update to the TD receiver and thereafter would combine the position information with the output from an air data dead-reckoning subsystem. The airfield instrument landing system was assumed to be ILS or AILS, as with CTOL and SST.

5.2.1 Navigation Aid Operational Requirement

Tables XXIX and XXX present a summary of the capability of each of the twelve system configurations to satisfy the operational requirement. In the tabulation:

+ → meets requirement
o → marginal
- → does not meet the requirement

Three systems - NAV SAT, LF/CW GBTD and LF-Pulsed GBTD - completely satisfy the performance requirements. The VOR/DME system and the PVOR/PDME system, when equipped for area navigation through integration with a course line computer, also meet the operational requirement.

TABLE XXIX
NAVIGATION REQUIREMENTS CHECKLIST - GBTD

NAV SYSTEM REQUIREMENT \ NAV SYSTEM	VLF/CW	LF/CW	LF/PULSED
NON-SATURABLE	+	+	+
MINIMIZE NAV FREQUENCY	+	+	+
LOS INDEPENDENT	+	+	+
AREA COVERAGE	+	+	+
REAL TIME	+	+	+
ALL WEATHER	o	+	+
MINIMAL NUMBER GROUND STATIONS	+	o	o
TIME INDEPENDENT	o	o	+
FLEXIBLE TO ATC ROUTE STRUCTURE/VECTOR	+	+	+
MAP REFERENCE	+	+	+
COMMON OUTPUT FORMAT*	+	+	+
GROWTH ORIENTED	o	+	+
ADAPTIVE FLIGHT PATH CAPABILITY*	+	+	+
GENERATE ATC SURVEILLANCE DATA**	+	+	+
COMPATIBLE WITH INFO NEEDS*	+	+	+
SATISFY ACCURACY CONSTRAINT	o	+	+

*Dependent upon onboard computer
**Dependent on data link message content

TABLE XXX
NAVIGATION REQUIREMENTS CHECKLIST - NAV SAT AND RHO-THETA

NAV SYSTEM REQUIREMENT \ NAV SYSTEM	VOR/ DME	PVOR/ PDME	VOR/ DME CLC	PVOR/ PDME CLC	NAV SAT	DIFF NAV SAT
NON-SATURABLE	-	-	+	+	o	o
MINIMIZE NAV FREQUENCY	-	-	-	-	+	+
LOS INDEPENDENT	-	-	-	-	+	+
AREA COVERAGE	-	-	o	o	+	+
REAL TIME	+	+	+	+	o	o
ALL WEATHER	+	+	+	+	+	+
MINIMAL NUMBER GROUND STATIONS	-	-	-	-	+	+
TIME INDEPENDENT	+	+	+	+	+	+
FLEXIBLE TO ATC ROUTE STRUCTURE/VECTOR	+	+	+	+	+	+
MAP REFERENCE	+	+	+	+	+	+
COMMON OUTPUT FORMAT	+	+	+	+	+	+
GROWTH ORIENTED	-	-	o	o	+	+
ADAPTIVE FLIGHT PATH CAPABILITY*	-	-	o	o	+	+
GENERATE ATC SURVEILLANCE DATA*	o	o	o	o	+	+
COMPATIBLE WITH INFO NEEDS*	+	+	+	+	+	+
SATISFY ACCURACY CONSTRAINT	-	+	-	+	+	+

*Dependent upon onboard computer
**Dependent on data link message content

5.2.2 Navigational Aid Accuracy Requirement

Figure 31 summarizes the accuracy that is attainable with the candidate navigational aids. (The details of the supporting analysis are presented in Section F.) The accuracy is expressed as the 3σ horizontal component. The spread on the system errors is caused by varying mission geometry, propagation conditions, conductivity conditions, or equipment specification. Superimposed on the accuracy envelope of the candidate systems are the navigation accuracy requirements (shown as a series of dashed lines), taken from Table XXVIII. The accuracy requirements are identified functionally in the right-hand margin, e.g., Climb-Descent, Holding, etc.

A 3σ navigation accuracy requirement of 0.5 nmi for all user aircraft operating in enroute congested airspace or terminal areas can be attained utilizing VOR/DME, NAV SAT and GBTD systems.

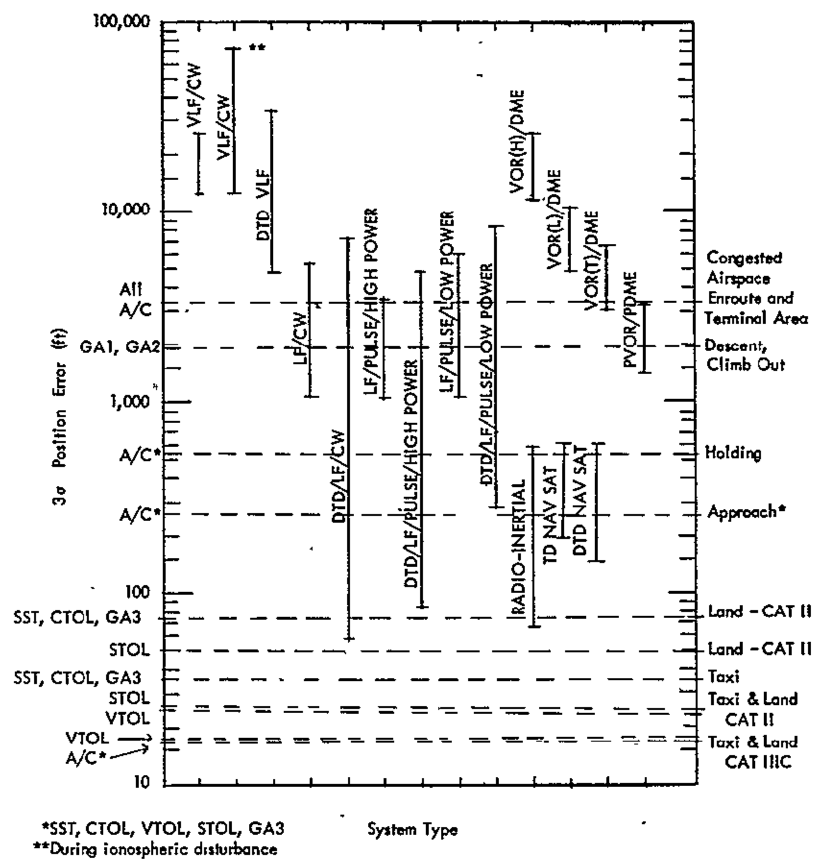


Figure 31. Summary of Navigation System Requirements - 1975-1985

The climb, descent and approach navigation accuracy requirements for general aviation are specified as 0.3 nmi. This capability can be met using PVOR/PDME, NAV SAT and the GBTD systems. Required accuracy of navigation for any arbitrarily established holding pattern (area navigation rather than radial navigation) is specified to be 0.12 nmi (3σ) for all user aircraft. The desired accuracy can be achieved with the differential time difference systems and with NAV SAT. Other GBTD systems and PVOR/PDME show marginal capability to supply the desired accuracy of information throughout the respective service areas.

The region of approach to landing is stated to be from 10 nmi out on final approach to the runway to a position 2 nmi out. Within this region, required accuracy of navigation information for all but GA1 and GA2 aircraft is 360 ft (3σ). Analysis indicates that this accuracy is attainable with the differential GBTD systems and the NAV SAT system. When integrated with velocity information from an IMU, the resulting radio-inertial differential time difference system would appear to improve accuracy to better than 75 ft, sufficient for CAT II-a landing requirements.

Typical approach and departure flight paths were selected for evaluation. The present-day New York TMA is used as the test model, since by 1980 approximately half of the major hubs will have to be capable of handling as much traffic as does New York today.

5.2.3.1 Steady State Navigation System Errors

Figure 32 shows a chart on which has been superimposed Time Difference (TD) contours typical of a GBTD LF-CW system. Figure 33 shows typical error contours for the LF-CW system. The accuracy parameters used were mean arrival time uncertainties of 0.1 microsecond with a correlation of zero. This approximately corresponds to daylight operation in reasonably good weather. The plot shows that a fairly large area around the New York TMA is serviced with TD information which is accurate to better than 200 ft. It must be kept in mind, however, that the error can be three or four times as great for operation at night during the winter.

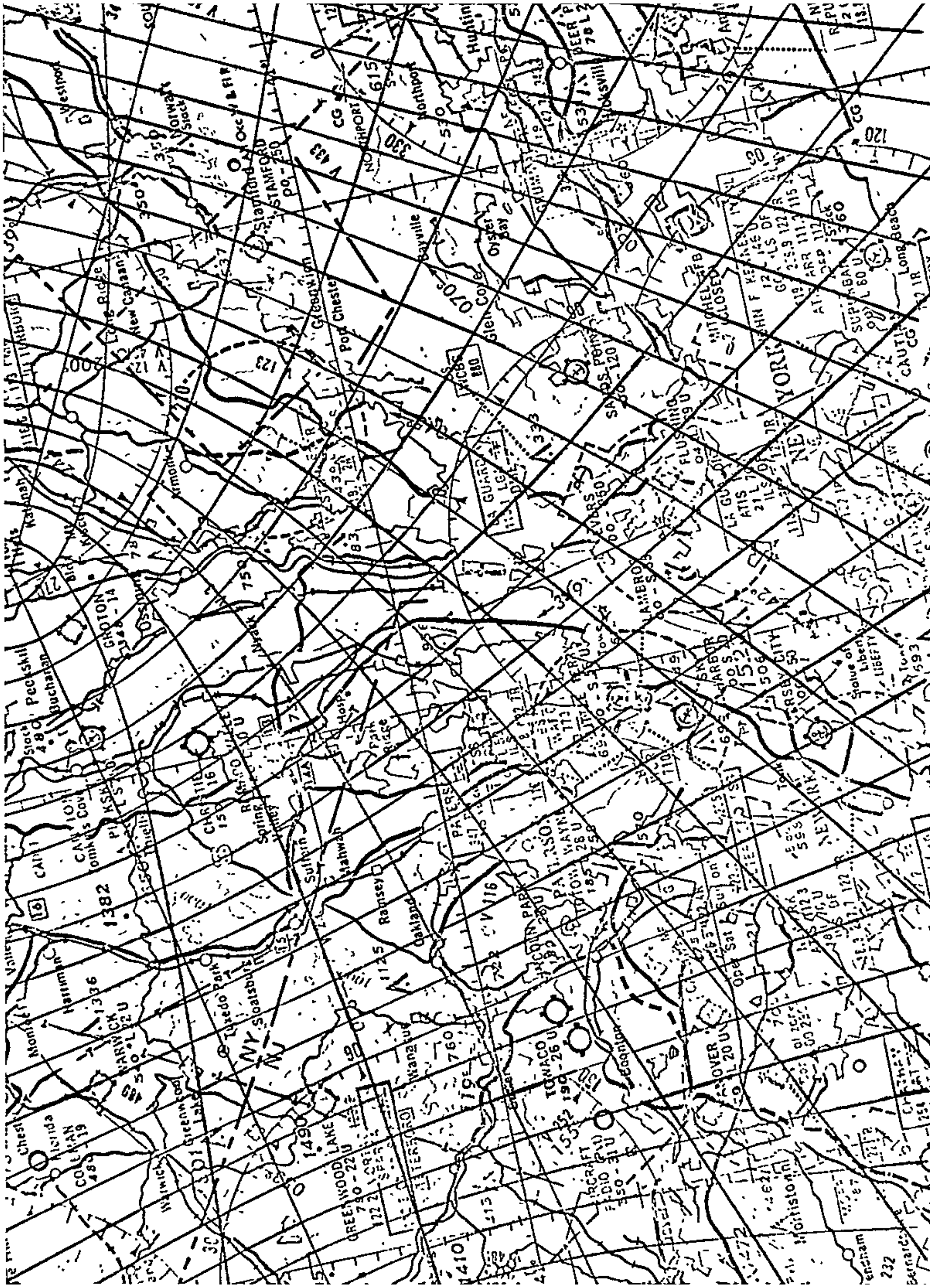


Figure 32. Time Difference Contours – LF CW System

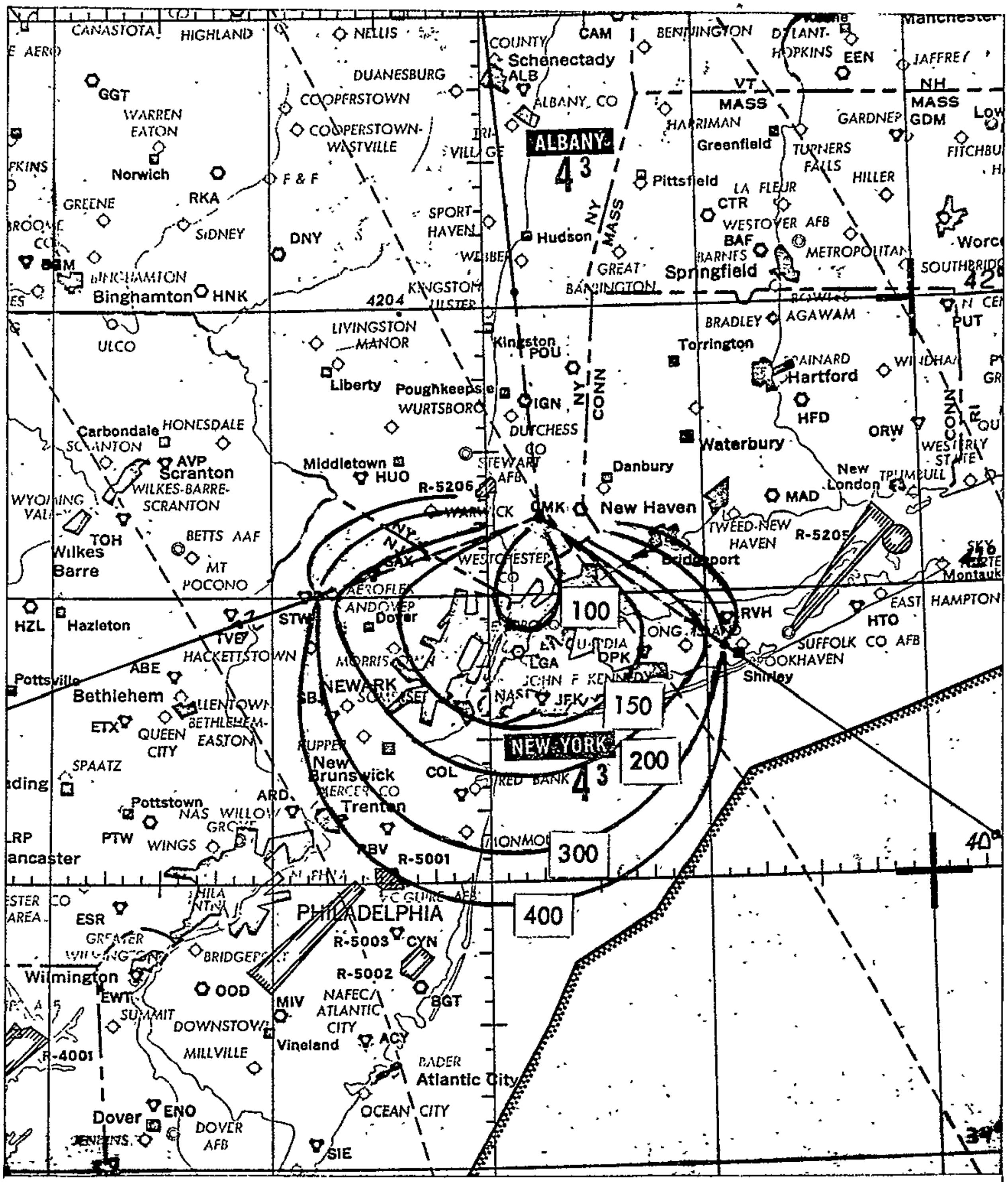


Figure 33. Typical GBTD LF Error Contours

Figure 34 shows spot error contours for a LF-CW GBTD system installed in the New York TMA (small circles) and a set of ellipses tied to the Colts Neck, Solberg, LaGuardia and Carmel VORTACS. A CLC system is assumed. The VOR azimuth error used was 2°, and the DME error was maximum (0.5 nmi or 3% of distance, whichever is the greater). The ellipse describes the rho-theta error. The resulting errors are given in feet and are 3σ (.997) values. Comparisons of errors for other area navigation systems - Omega, NAV SAT and Loran - are shown. These errors will be essentially constant throughout the New York region.

The error contours for a precision VOR/DME (PVOR, PDME) system is shown in Figure 35. VOR azimuth error is assumed to be 0.5°; DME error assumed is a maximum value (0.1 nmi, or 1% of distance).

The analysis pictured in Figures 34 and 35 took account of typical cockpit procedures which might be employed by users of the New York TMA. It will be seen that substantial variation can be experienced in the accuracy of position data as a function of relationship to a given facility. These relationships will have an effect on selection and use of surveillance data relayed from aircraft to ground. For example:

(1) CTOL Approach to JFK - This track shows a close approach to the Colts Neck VORTAC prior to intercepting the JFK ILS. As a result, there is little variation in the error ellipse.

(2) CTOL Departure - A similar pattern is developed for the climb out from JFK if the pilot uses LGA until the aircraft is at the halfway point between LGA and Carmel, about 12 miles. Note the fairly constant distribution of error out to point 10, the point of changeover to Carmel.

(3) GA1 and GA2 Approach - This track shows a similar situation. The errors for the Solberg VORTAC are shown (dotted) concentric to the LaGuardia error ellipse. The smallest circles at the center of each of the ellipsoids depict the position accuracy of the Decca chain.

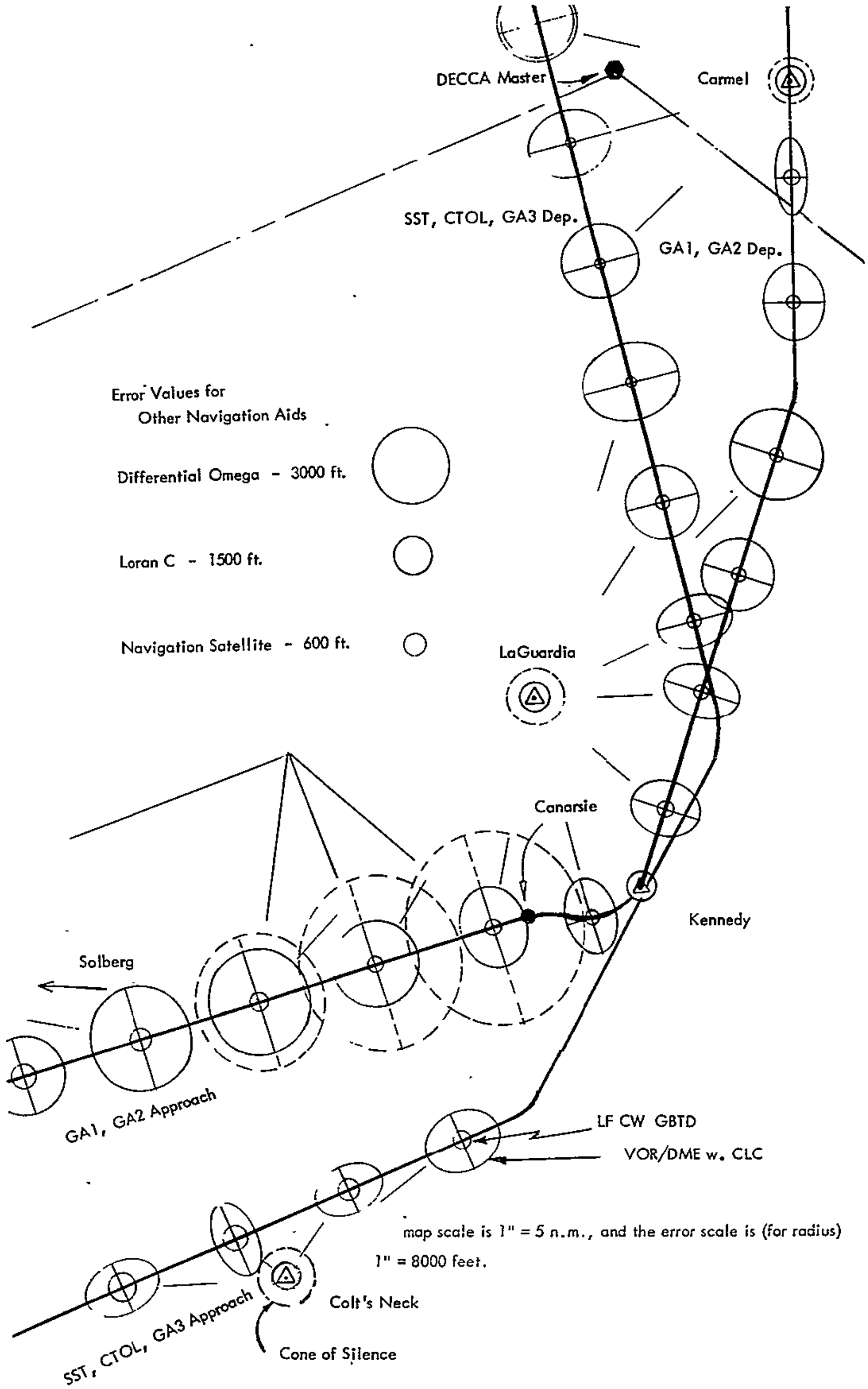


Figure 34. Errors in Terminal Area Navigation - (VOR/DME Reference)

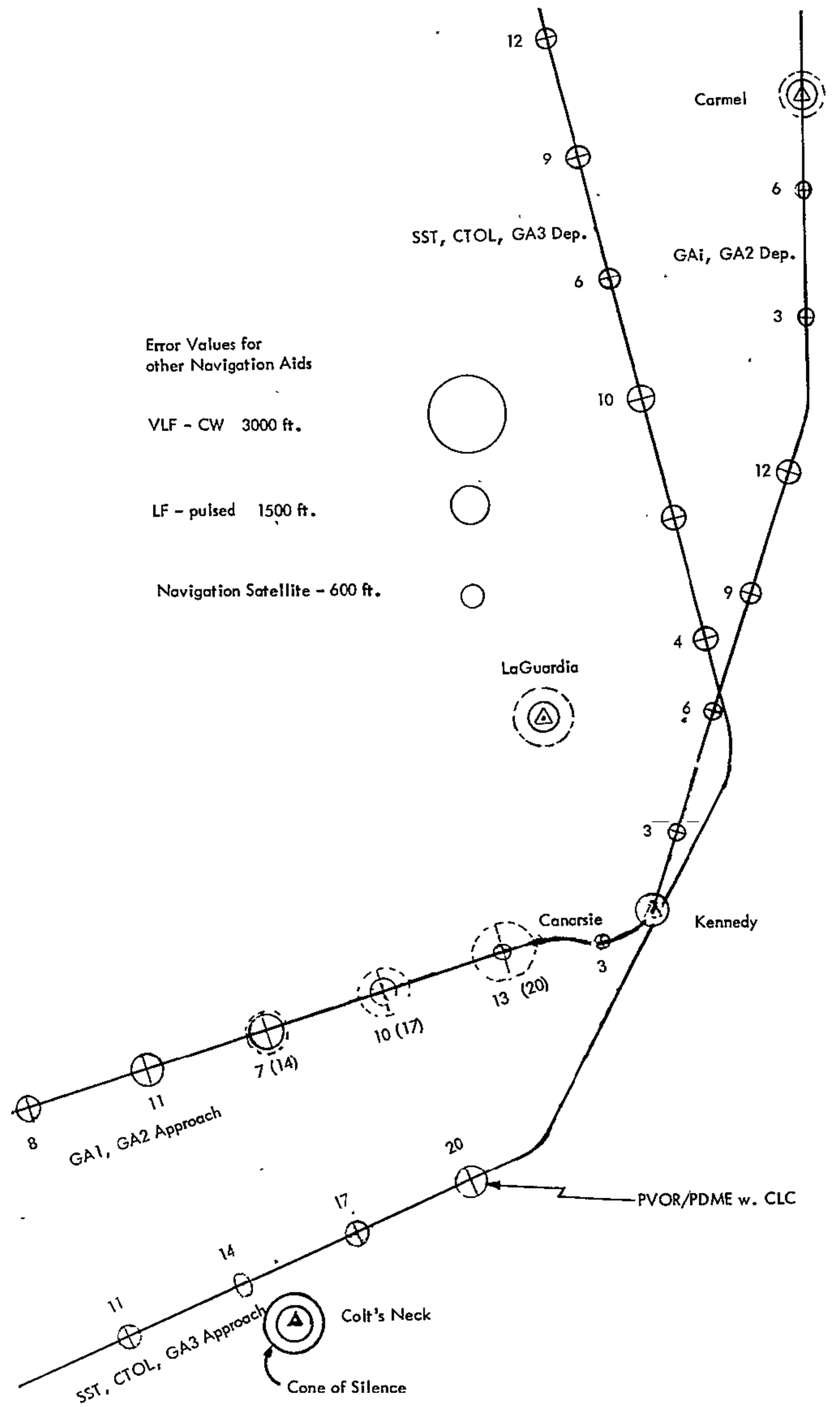


Figure 35. Errors in Terminal Area Navigation - (PVOR/PDME Reference)

(4) GA1 and GA2 Departure - This track illustrates the effect of crossing the cone of silence, the dotted circle at Carmel. This error will be significant to the ground based surveillance system.

It is obvious that the GBTD chain provides a significant margin of increased accuracy over the ordinary VOR/DME fixes. However, the error ellipse for a precision VOR/DME system compares favorably with those of the hyperbolic system. The PVOR/PDME is subject to LOS restrictions and multi-path effects, however.

Two of the tracks in particular show the limitations of present DME systems. DME is stated to be accurate to 0.5 nmi (3σ), out to 17 nmi from the facility, and thereafter to be accurate to 3% of distance from the facility. Beyond approximately 15 miles, the error in azimuth causes the major axis of the error ellipse to shift to the cross track direction. Within 15 miles, the ellipses on the CTOL approach and the GA1 and GA2 DEP tracks elongate towards the VORTAC as the aircraft approaches the station.

Notice also the large size of the error circle at the last point on CTOL DEP2 as compared with the error circle on the immediately preceding position. This increase reflects the fact that the aircraft has transitioned to the region of the baseline extension.

5.3 ADVANCED AREA NAVIGATION SYSTEMS

Tables XXXI and XXXII summarize the qualitative requirements data in terms of flight phase and candidate navigation concepts. The data tabulated in these tables holds a one to one correspondence with the system requirement data tabulated in Table XXVIII. The qualitative data shows the acceptability for enroute, climb out, descent and terminal area flight in the 1975-1985 time frame of GBTD (LF CW, LF Pulse), PVOR/PDME and NAV SAT. As approach aids, NAV SAT, differential NAV SAT, differential LF CW and differential pulsed systems are candidates. These candidate systems are evaluated in varied communication, navigation and identification systems tied to the Flight Plan Reference traffic control concept.

Because of marginal acceptability and the need for a baseline system, VOR/DME in the area navigation configuration is also evaluated.

NAV SAT, GBTD and precision rho-theta navigation systems can fulfill the desired operational capability and also comply with the 1975-1985 horizontal accuracy requirement. In addition to the system navigation and communication requirements, the significant effects on pilot workload must be assessed. Pilot workload is evaluated in Section 6 for varying levels of system automation, ground and airborne,

TABLE XXXI
NAVIGATION REQUIREMENTS SUMMARY - SYSTEM PERFORMANCE

	DISTANCE TO TERMINAL	VOR/ DME	PVOR/ PDME	VOR/ DME/ CLC	PVOR/ PDME CLC	NAV SAT	DIFF NAV SAT	
TAXI	0	-	-	-	-	-	-	
TAKE-OFF	0-2 nmi	-	-	-	-	-	-	
CLIMB-OUT	2-50 nmi	o	+	o	+	+	+	
ENROUTE - LOW	>25 nmi	o	+	o	+	+	NA	
ENROUTE - HIGH	>50 nmi	o	+	o	+	+	NA	
ARRIVAL	25-50 nmi	o	+	o	+	+	NA	
DESCENT	7-50 nmi	o	+	-	+	+	+	
APPROACH	7-10 nmi	-	-	-	-	+	+	
LAND	0-2 nmi	-	-	-	-	-	-	
TAXI	0	-	-	-	-	-	-	
HOLDING	50 nmi	-	-	-	-	+	NA	

\+ meets requirement
\- does not meet requirement
o marginal
NA not applicable

for the advanced area navigation systems:

(1) NAV SAT

(2) GBTD

(3) precision rho-theta; and

(4) differential NAV SAT

(5) differential GBTD

The specific enroute, approach and landing airborne configuration, including receivers, computers, data link, displays and area navigation systems, is discussed in Section 6.3.

TABLE XXXII
NAVIGATION REQUIREMENTS SUMMARY - SYSTEM PERFORMANCE

	DISTANCE TO TERMINAL	VLF/CW/ TD	VLF/CW/ DTD	LF/CW/ TD	LF/CW/ DTD	LF/PULSE/ TD	LF/PULSE DTD
TAXI	0	-	-	-	-	-	-
TAKE-OFF	0-2 nmi	-	-	-	-	-	-
CLIMB-OUT	2-50 nmi	-	o	+	+ → NA	+	+ → NA
ENROUTE - LOW	>25 nmi	-	o	+	NA	+	NA
ENROUTE - HIGH	>50 nmi	-	-	+	NA	+	NA
ARRIVAL	25-50 nmi	-	o	+	NA	+	NA
DESCENT	7-50 nmi	-	o	+	o	+	o
APPROACH	7-10 nmi	-	-	o	+	o	+
LAND	0-2 nmi	-	-	-	o →	-	o → -
TAXI	0	-	-	-	-	-	-
HOLDING	50 nmi	-	-	+	NA	+	NA

\+ meets requirement
\- does not meet requirement
o marginal
NA not applicable

SECTION 6

SYSTEM AUTOMATION

6.0 SUMMARY

This section presents the results of the pilot workload analysis. It combines the rationale of the advanced navigation/traffic control system (Section 4), the candidate area navigation systems (Section 5), and the user mission profiles (Section 2), with the objective of determining cockpit workload improvements through increased automation. It configures the promising area navigation aids such as NAVSAT, GBTD, and precision rho-theta systems into different levels of system automation, and evaluates workload when engaged with the ATC Flight Plan Reference system. This section exercises specific airborne avionics equipments, reflecting general aviation and aircarrier usage, through the Event Sequence Diagrams (Appendix A) of the Flight Plan Reference ATC system. It trades off pilot workload and system automation.

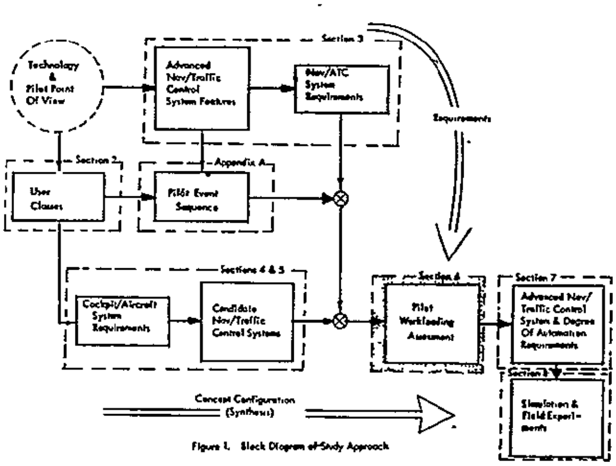


Figure 1. Block Diagram of Study Approach

The system automation analysis considers workload induced on both the general aviation and aircarrier pilot and copilot. Generally, automatic flight control minimizes the aircarrier VTOL, STOL, CTOL, SST and GA3 general aviation flight-crew workload caused by enroute control and monitor tasks. But, terminal area workload is high and consequently high levels of comm. and nav. automation are needed. In contrast, integration of the GA1 and GA2 pilot into the 1975-1985 densely populated airspace requires extensive automation of the navigation, communication, and control functions, particularly automatic flight control.

The Flight Plan Reference system promotes efficient utilization of the communication channel. Automation of the typical general aviation VFR communications and air carrier IFR messages -- such as position report, command data uplink, and advisories -- could reduce workload by as much as 91 percent enroute and 56 percent in the terminal area.

For the GA1 and GA2 pilot, automation can provide significant improvements in performance at no increase in workload, a necessary condition for flight in the 1975 to 1985 terminal area. Under VFR operation in congested, controlled airspace, automation permits the general aviation pilot to successfully manage all aspects of his flight. An automated system for the GA1 pilot provides flexibility and minimum workload in terminal area and enroute flight and also on the total mission. This automated airborne system uses either the NAVSAT or GBTD navaid. Suitable changes must be made in the ground system.

The airborne system incorporates a time difference receiver with automatic acquisition and track. A minimum capacity, VHF data link downlinks time and time-difference information. The uplink returns distance and desired track to the next scheduled waypoint, to the destination, or to a general location as specified in the Flight Plan Reference. A local aeronautical chart with GBTD contours and a handheld DR computation aid complete the systems. Voice is retained for backup communications.

The GA2 pilot, operating with more expensive and sophisticated electronic equipment, maintains maximum flexibility and minimum workload with his more extensively automated system. These systems reduce workload by 50 percent, 33 percent, and 26 percent respectively, as compared to the GA1 communication and navigation management tasks. A moving-map display further reduces workload by 10 percent.

Pilot workload/system automation studies of the aircarrier and GA3 vehicles take the same format. The short haul VTOL, STOL, and GA3 aircraft--and the long haul CTOL and SST aircraft--make extensive use of on-board general-purpose computers, and datalink; and as a primary navigation system they use NAVSAT, GBTD, precision rho-theta. Each system incorporates a control/display subsystem--either an "aircarrier control display unit" or a pictorial, moving-map display. The computers incorporate a vertical navigation channel. The primary communications link is a VHF datalink. Voice is a backup. The airborne systems perform as a complement to the Flight Plan Reference system. Landing systems also use the above computer.

The workload analysis justifies the use of the Flight Plan Reference ATC concept. Workload tradeoffs include total inflight navigation management, inflight navigation management automation benefits, and navigation workload automation benefits. As an example, the navigation management benefits that can be achieved by implementing the Flight Plan Reference system with an area navigation (GBTD or NAVSAT) system and a flight plan reference computer, reduces workload by 9 percent with a programmed flight plan, 9 percent with coded terminal area waypoints, and 46 percent with the use of Limit Logic.

Other extensive tradeoff analysis of datalink message automation, landing system automation, a pictorial moving map display with command signal automation, etc., justify the Flight Plan Reference Concept.

SECTION 6

SYSTEM AUTOMATION

The pilot workload analysis was the focal point of the NAVTRACS study. The study requirement was to assess performance of the advanced/navigation traffic control system from the viewpoint of the pilot. Recognition of the cockpit point of view infers that the suggested traffic control system as a minimum should not increase workload of the pilot, regardless of level of proficiency. Obviously the proposed system had to be capable of accommodating all user vehicles forecast to be operational in the time frame of interest. Any areas of activity which necessitated an unreasonable change in pilot workload became candidates for automation, and as a result, represent logical recommendations for new technology or research and development.

The workload analysis required development of assumptions about almost every element of the future system: premises were required regarding organization of the future ATC system, acceptable procedures, performance of the vehicles, and availability of avionics equipment. Much data was taken from NASA, USAF and FAA supported studies. Equipment features were postulated from ARINC specifications, from documents supplied by avionics manufacturers, and from discussions undertaken with professional pilots, navigators, and general aviation pilots. Where present equipment did not provide for necessary control display operations (of future equipment), "straw man" panels and operational procedures were created.

Figure 36 illustrates the methodology utilized in the workload analysis.

Event sequence diagrams (See Appendix A) were constructed to relate mission events, pilot tasks, and aircraft monitor and control functions with ATC. Each flight profile was divided into its nine phases: pre-flight, taxi, take off, climb out, departure, enroute, arrival, approach and land. The event sequence diagrams identify and relate the fundamental pilot tasks of control and monitor of aircraft systems to communication events, and to managing the aircraft navigation.

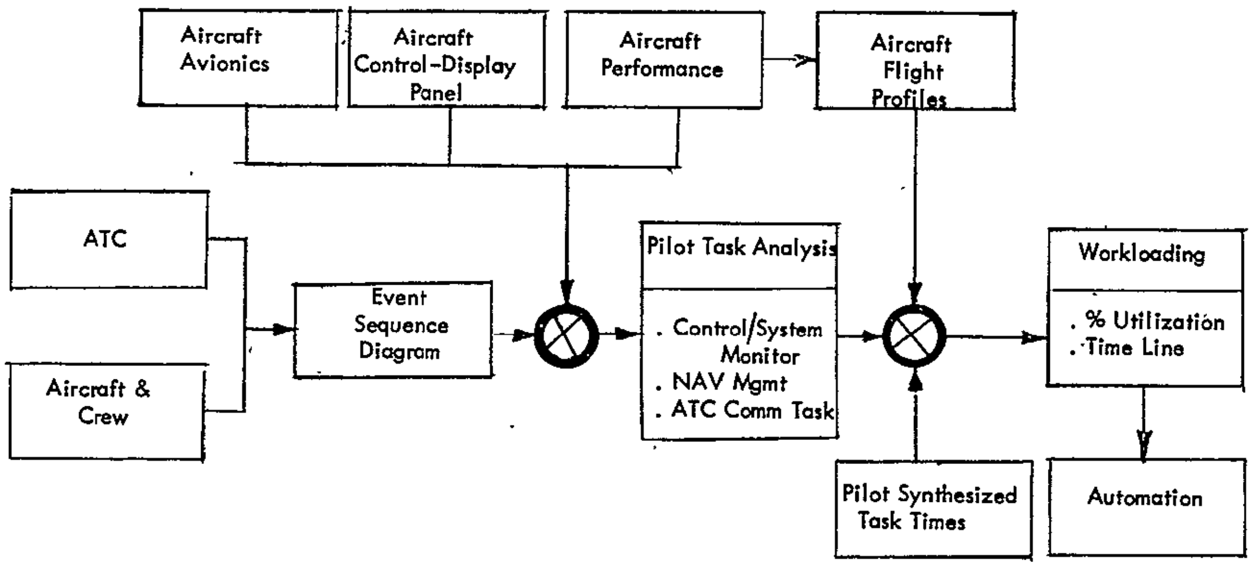


Figure 36. Pilot Workloading Analysis Methodology

The aircraft flight profiles, structured in Section 2, relate the pilot activities to a time base thus making possible an evaluation of workload in the context of a complete ATC system. The time base showed when a task was to be performed and the interval of time during which it had to be completed.

Each significant event was then correlated with a pilot task, the elements of the task identified and a set of task times prepared. Wherever alternatives (equipments) were available, the operator response measurements are repeated.

Pilot workload was specified in terms of two quantitites - percent utilization and time to accomplish the task. The total workload estimate, when tied to the event sequence diagrams and aircraft flight profiles provides a means by which to identify automation needs.

6.1 NAVIGATION/ATC EVENT SEQUENCE DIAGRAM

Appendix A contains the event sequence diagrams for the advanced navigation/ ATC systems.* There are four major topics treated in the diagrams:

Figure A-2	Navigation Management Event Sequence Diagrams
Figure A-3	VFR Event Sequence Diagrams
Figure A-4	IFR Event Sequence Diagrams
Figure A-5	All Weather Landing Event Sequence Diagrams.

The VFR and IFR Event Sequence diagrams describe a typical flight, beginning with the pre-flight briefing and ending with taxi-in and system shutdown. These diagrams illustrate flight phase relationships, the navigation and communication management functions, and aircraft control and monitor tasks. The diagrams indicate the cognizant traffic control and surveillance unit, and show the surveillance technique--direct communication, ASDE, interrogation. Communication requirements related to control of traffic and provision of required surveillance information dictate the air-to-ground and ground-to-air communications events. Manual and automatic flight control system utilization are shown on the aircraft control and monitor ESD. The ESDs which describe the navigation management tasks show steps necessary to derive aircraft steering signals, to maintain the aircraft on its assigned flight path, or to generate surveillance data for use by ATC.

The VFR and IFR Event Sequence Diagrams integrate the general navigation management functions. The specific tasks vary with the particular aircraft avionics, control/display, and operational procedures employed. The pilot control and monitor tasks are generalized, specific tasks vary with each different type of vehicle. The communication tasks are general and depend upon the level of automation in the data link, direct communications equipment. Because of the generalization of the Event Sequence Diagrams, they can be utilized for analysis of any combination of navigation, communication, aircraft control and monitor equipments and for any level of system automation. Figure 37 illustrates the organization

*The organization is illustrated in Figure 37.

6.1.1 Navigation Management Event Sequence Diagrams

Figure A-2, Appendix A, shows the navigation management event sequence diagram. The diagrams are serial, operational flow diagrams showing tasks essential to accomplishment of the navigation management function. The on-line processing functions generate data for the parallel functions of communications and aircraft control and monitor.

The navigation management function includes the tasks listed below. Depending on the user, these functions, as shown in Appendix A, Figure A-2 , may be manual or automated, and may or may not be performed consciously and regularly.

(1) Review current meteorological (met) forecast: outputs are wind component along track, wind component cross track, temperature, regions of possible icing, and other hazardous weather.

(2) Initial set-up of system: initiate navigation system operation; this task includes switch on, system alignment, data insertion. instrument calibration, etc.

(3) Review current leg: determine desired course, distance to go, altitude requirements.

(4) Program next waypoint: insert data for next leg (terminal area or enroute).

(5) Reprogram system - inflight: insert any required revision to flight plan data.

(6) Acquire position data: produces position or error information to generate steering signals.

(7) Update steering signal: output is track angle error, cross track distance, distance to go.

(8) Check flight path status: output is revised track angle error, cross track distance, command altitude, power setting.

(9) Check flight plan status: confirm Limit Logic, revise steering error signal.

(10) Prepare report: assemble and store standard report data and/or abbreviated report data for surveillance link transmission to ATC.

The pilot or computer performs the navigation management tasks in serial fashion throughout the entire flight profile.

6.1.2 VFR Event Sequence Diagram

Figure 37 portrays the Event Sequence Diagram format. Appendix A, Figure A-3 contains the VFR Event Sequence Diagram. This diagram illustrates the GA1 and GA2 aircraft operation. The GA1 or GA2 pilot without the assistance of a copilot performs the navigation, communication and control tasks for the entire flight profile. Aircraft profile events such as "complete turn", "climb to cruise altitude", "reach cruise altitude",

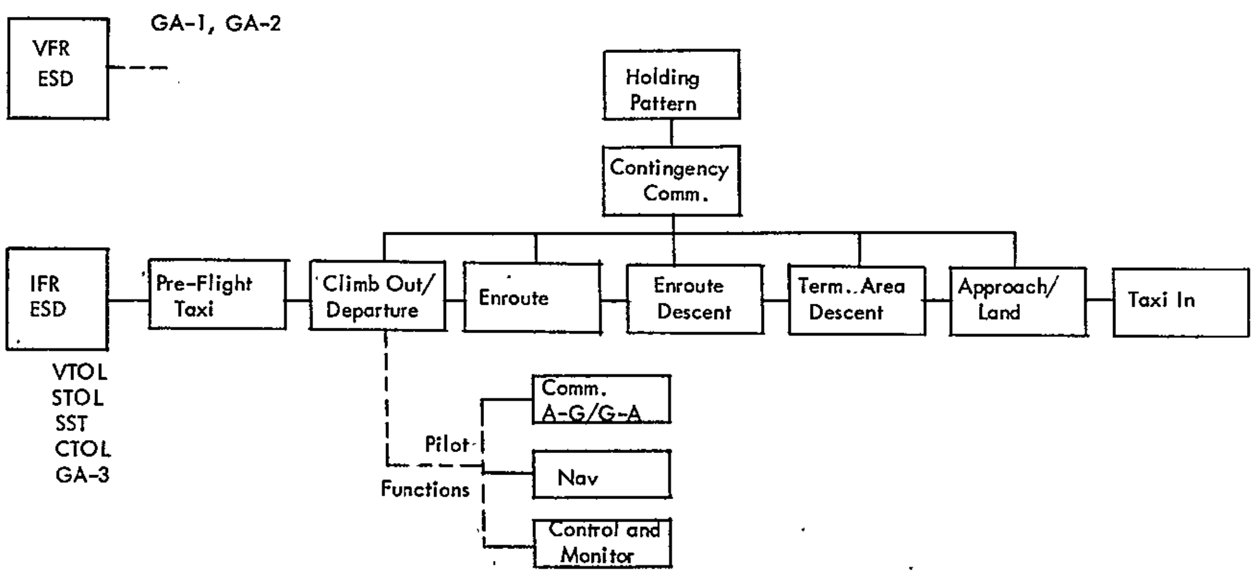


Figure 37. Organization of the Pilot/ATC Event Sequence Diagram

trigger the communication and navigation events. The Air-to-Ground and Ground-to-Air communication functions relate the aircraft to appropriate ATC units such as "Enroute surveillance", "descent surveillance", Approach Control and Tower. The navigation management function are performed in parallel with the communication and control functions.

The VFR Event Sequence Diagram shows the dependence of the Flight Plan Reference System and Limit Logic functions to successful acquisition of surveillance data. Take off, approach and landing are performed as a standard VFR operation.

6.1.3 IFR Flight Plan Event Sequence Diagram

The events described in the IFR Flight Plan ESD illustrate operations for five aircraft types, VTOL, STOL, SST, CTOL and GA3. The air-to-ground and ground-to-air communications are identified as in the preceding set. The method of relaying surveillance information; voice, digital data link, or surveillance radar; is also indicated. The communication, navigation and control tasks are performed in parallel, as in the previous set. The timing of the tasks is keyed to events in the aircraft control channel. Provision for contingency communications is made on all flight profiles. A contingency communication event occurs if the Limit Logic is exceeded, or if the ground-to-air channel is exercised. Entry to a request to enter a holding pattern is initiated through the contingency communcation channel.

6.1.4 Utilization of Event Sequence Diagrams

The event sequence diagrams are utilized in the pilot workload analysis. Aircraft flight profiles are documented in Section 2, and provide the time base input to the event sequence diagram. In the following sections, general aviation, VTOL, STOL and other air carrier aircraft, the conceptual ATC system, the postulated aircraft avionics, the area navigation systems, the approach and landing systems are exercised to determine pilot workload in terms of percent utilization and task time.

6.2 PILOT TASK ANALYSIS

The pilot workload analysis utilized a model of the human operator. The pilot, copilot and crew were treated as essential system components in the advanced navigation traffic control system. The essential tasks performed by the crew includes:

(1) aircraft control and systems monitor functions
(2) navigation management
(3) communications.

Pilot and crew workload were assessed by noting percentage of operator utilization during the performance of a task. Two figures of merit used to quantify workload were:

(1) task time, and
(2) percent of operator utilization.

The objective of the workload analysis in the NAVTRACS program was to determine on a relative scale the trade-off values of different system configurations. No absolute measure of workload was sought.

6.2.1 Pilot/Copilot, Crew Model

The workload methodology, applied to the navigation management tasks, permitted assessment of the utilization of the operator's manual, visual and aural (voice) faculties. The workload methodology explicitly evaluates the percent utilization of the operator in the performance of these tasks. Implicitly considered in evaluation of task times were such factors as:

(1) operator proficiency,
(2) operator stress level ,
(3) operator fatique,
(4) task criticality,
(5) task difficulty.

The tasks and related workload measurements were critiqued in depth by

representatives of the five groups listed below.

(1) General Aviation Pilots.

(2) Military Pilots..

(3) Military Navigators.

(4) Air Carrier Pilots.

(5) Air Carrier Navigators.

The synthesized task times were generated for particular man/machine functions during particular portions of the aircraft flight phase. The evaluation assumed a trained, motivated, alert operator to be performing the tasks.

Appendix D summarizes the workload methodology. It presents the results of the analysis as applied to the current navigation/ATC system. A system in which a minimum of automation is present was postulated for the base line measurement. Message content of all communications is given for typical IFR and VFR flights.. The baseline pilot and copilot control and visual monitoring tasks for seven aircraft types (VTOL, STOL, SST, CTOL, GA3, GA2, and GA1 aircraft) are also summarized in Appendix D.

6.2.2 Pilot/Copilot Workload, Minimum Level of Automation

6.2.2.1 Control and Monitor Task

There is a relatively fixed level of work performed oy the pilot and/or copilot in control and monitor of the flight path of the aircraft. Quantification of this workload permits one to construct a baseline of task times and pilot utilization as a percentage of his total capability or capacity to do work at a particular instant. On top of this nominal load is placed the precent utilization for the navigation management and communication management functions. Figures 38 through 46 show crew workload for the mission profiles specified in Section 2. It is to be emphasized that the workload is a relative figure of merit. The task-loading depicted in these illustrations pertains to the control and monitor functions only. In hypothetical automated navigation/ATC system the pilot would be required only to fly the aircraft, thus greatly reducing total workload.

6.2.2.1.1 VTOL Pilot and Copilot

Figures 38 and 39 show VTOL pilot and copilot workload respectively. During the enroute flight phase, the automatic flight control system assumed to be installed on the VTOL aircraft reduces workload to a level such that the addition of navigation and communication management functions does not increase workload beyond a reasonable level. Time is available for inserting vector waypoints, managing onboard computer functions, and for modifying flight plans. The relatively short period of time

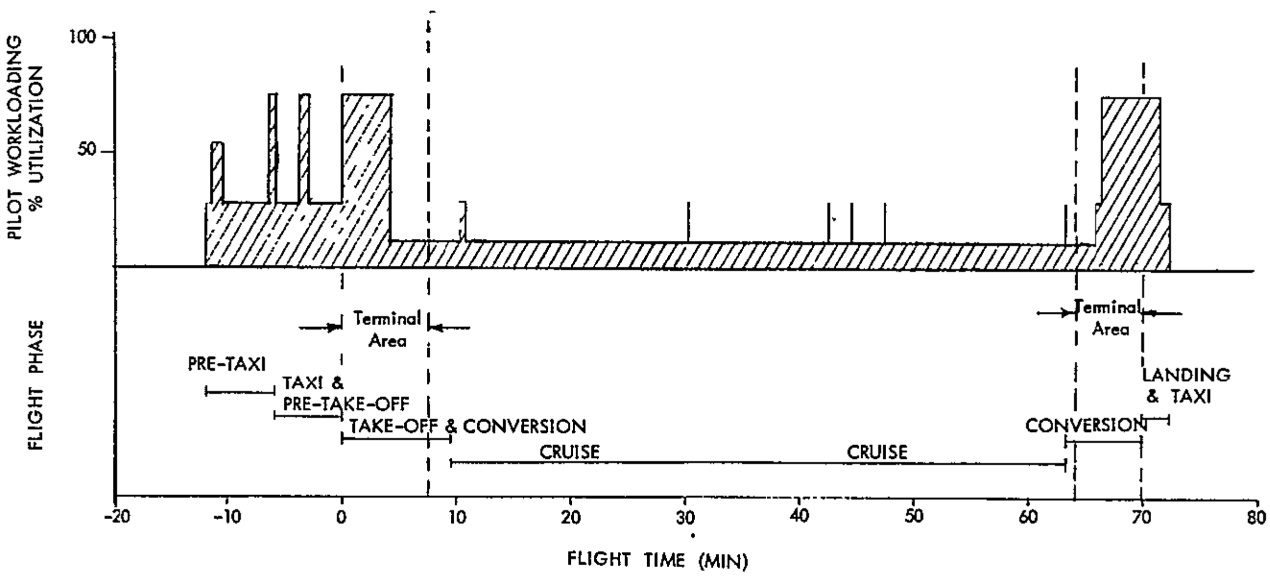


Figure 38 VTOL Pilot Workloading

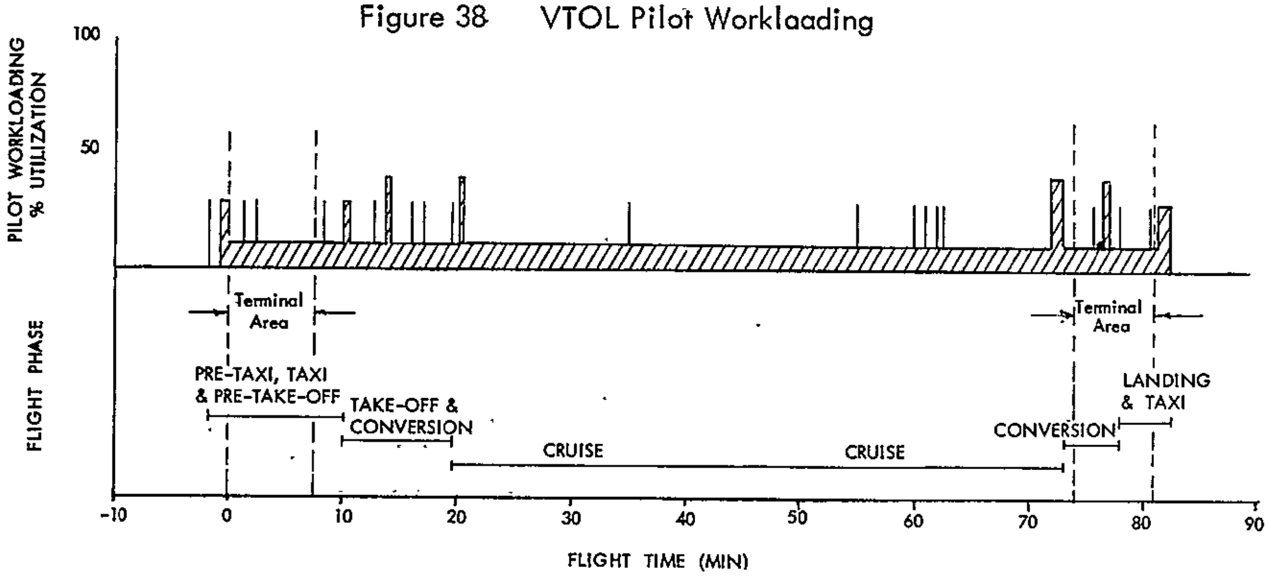


Figure 39 VTOL Copilot Workloading

spent in the terminal area during an approach or departure causes the apparent level of workload during that period to be appreciably higher than for other classes of aircraft or for the enroute phase of flight. During terminal area operations, navigation and communication management functions must be reduced to a minimal level. Consequently, a high level of automation is needed, and any unnecessary tasks such as insertion of vector waypoints and flight plan revisions should be completed prior to penetration of the terminal area.

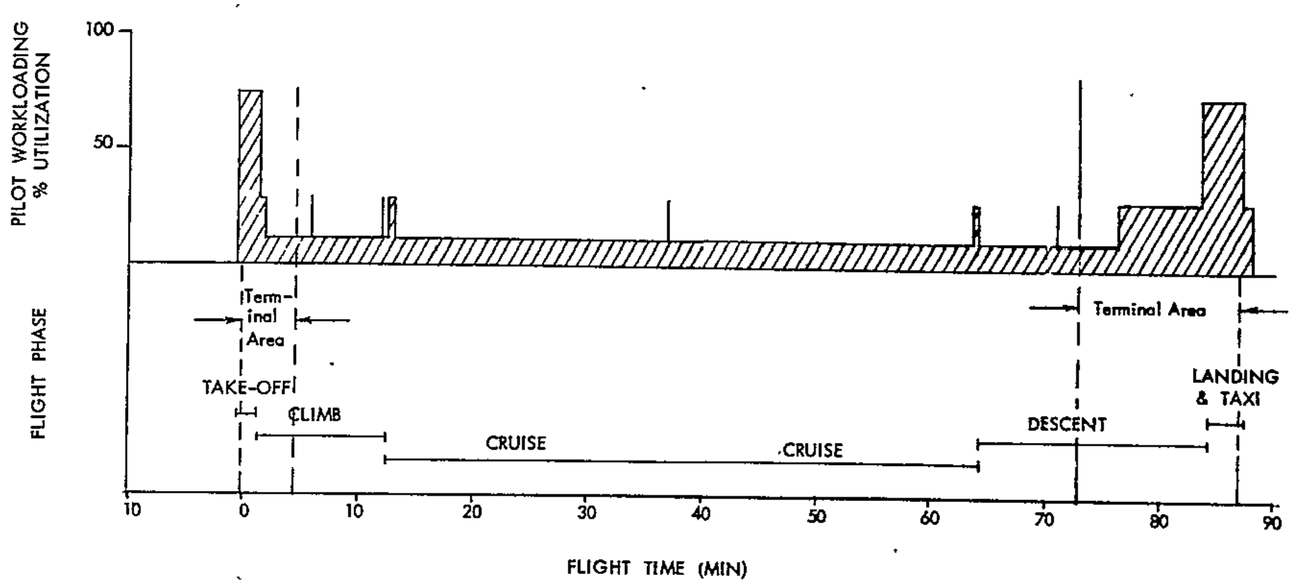


Figure 40 STOL Pilot Workloading

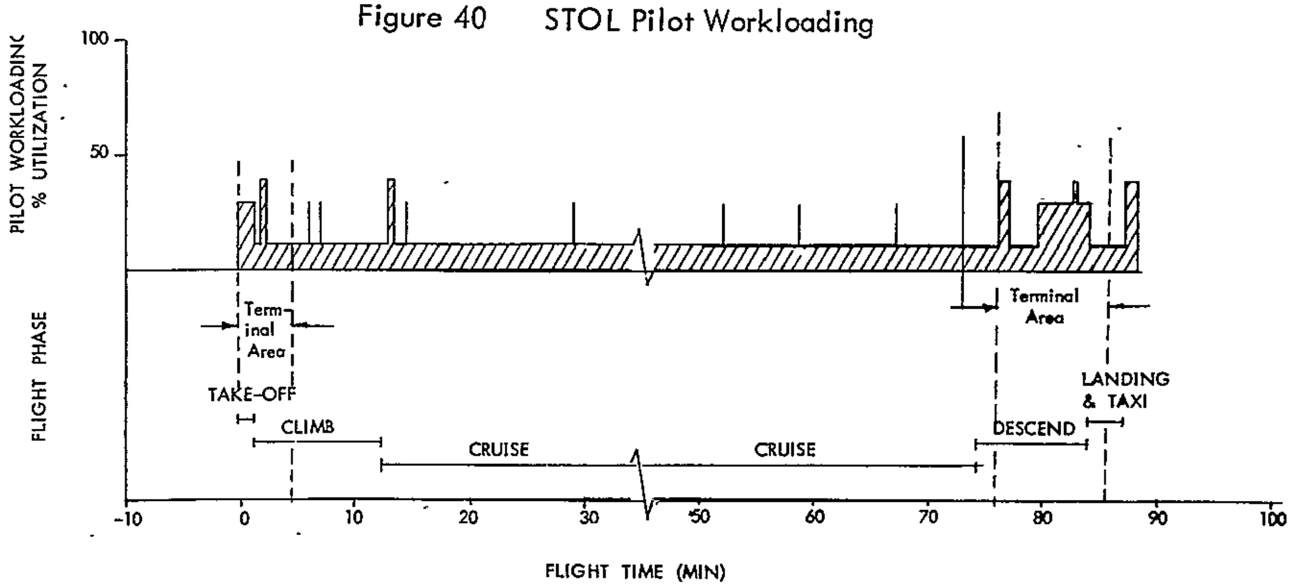


Figure 41 STOL Copilot Workloading

As a consequence, the ATC unit should forecast clearance and flight path malfunctions, and any vector or waypoint sequence requirements prior to entry to the terminal area.

6.2.2.1.2 STOL Pilot and Copilot

Figures 40 and 41 illustrate STOL aircraft pilot and copilot workload respectively. During the enroute phase, pilot workload is minimal becuase of extensive use of automatic

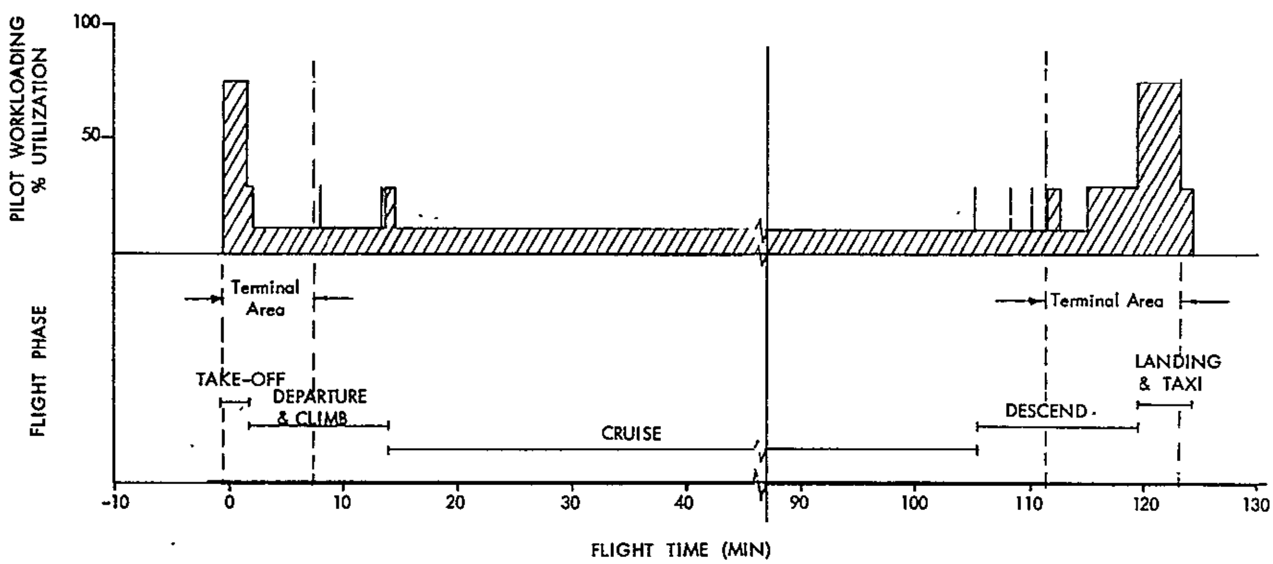


Figure 42 CTOL (GA3) Pilot Workloading

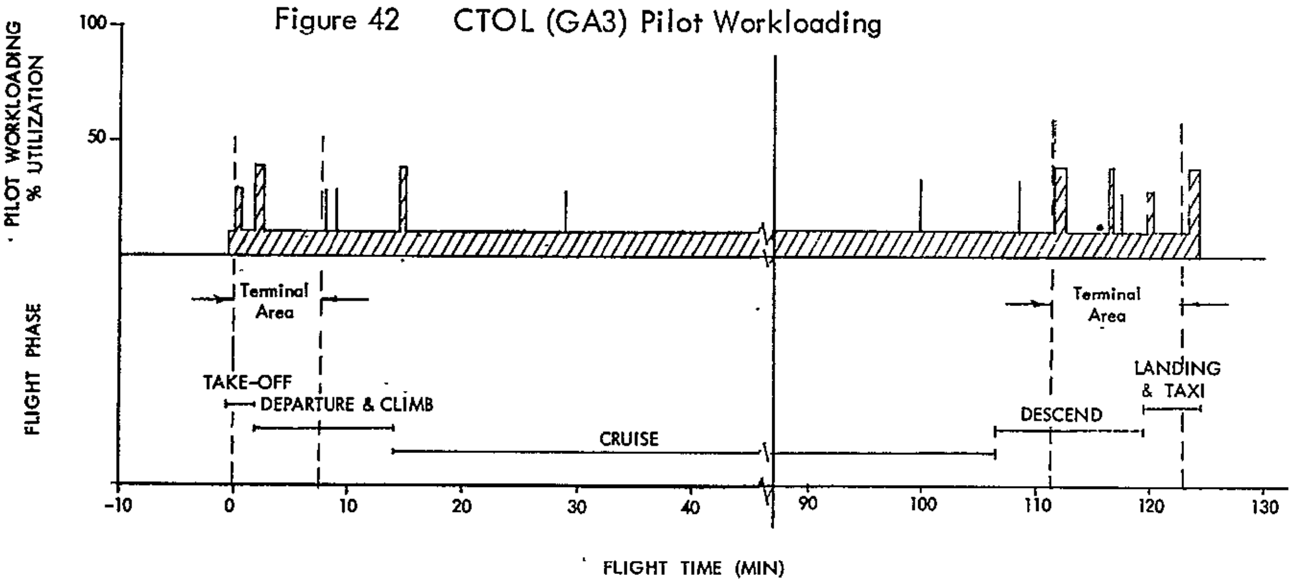


Figure 43 CTOL (GA3) Copilot Workloading

flight control. Thus the pilot and copilot are able to perform navigation management and communication management functions enroute without difficulty, and to prepare for entry into the terminal area with a minimum task-loading.

Terminal area workload is high, therefore navigation and communication management functions should be minimized. Utilization of a computer coupled with data link facilities can reduce the workload, but the proposed sequence of vectors and or waypoints to be used by ATC in the terminal area to obtain flow control should be known prior to

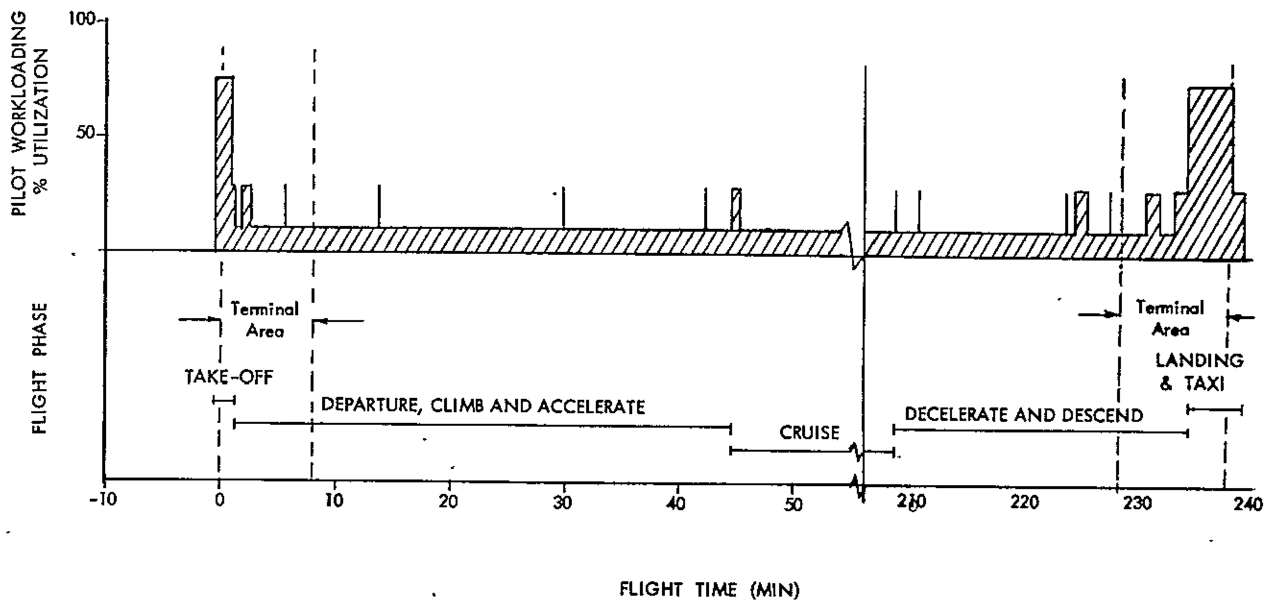


Figure 44 SST Pilot Workloading

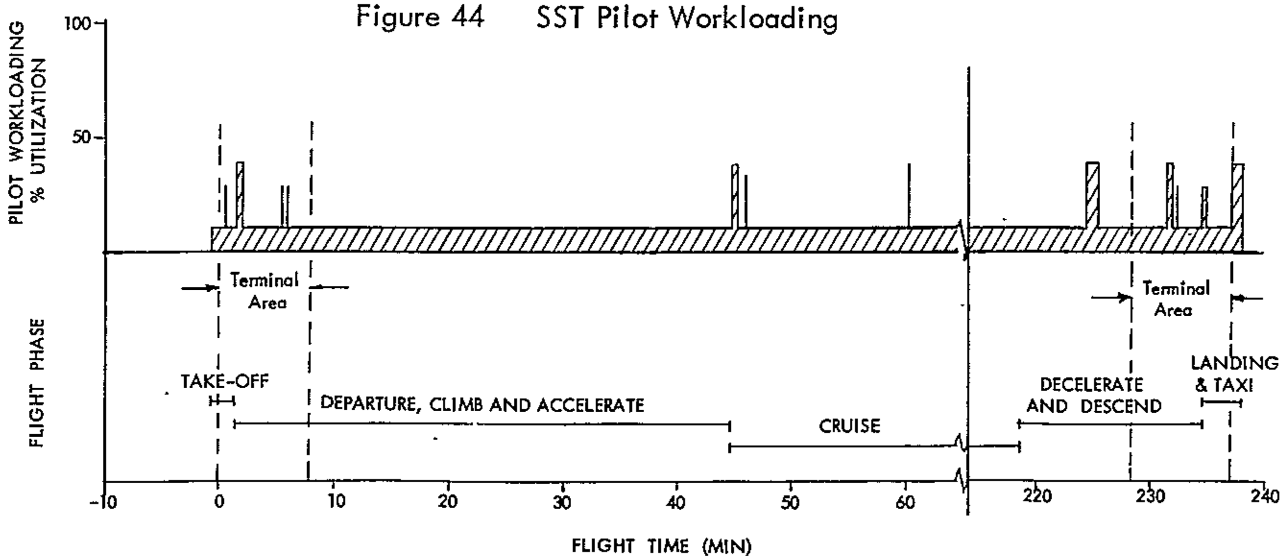


Figure 45 SST Copilot Workloading

penetration of the TMA by the aircraft. Delivery of expected routing and required time of arrival should be scheduled by ATC and forecast to the aircraft while it is enroute, to reduce the difficulty of navigation and to minimize cockpit workload.

6.2.2.1.3 CTOL, GA3 and SST Pilot and Copilot

Figures 42 through 45 show CTOL, GA3 and SST pilot and copilot workload during terminal area operations and during the enroute portion of the flight. As stated in the two previous subsections describing VTOL and STOL problems, advance knowledge of expected tracks in the terminal area, or special waypoints, is a system-requirement if area navigation is to become a viable concept. It is desireable to automate the navigation and communication management tasks associated with operation in the terminal area in order to keep workload at a reasonable level, whereas workload in the enroute base is not critical.

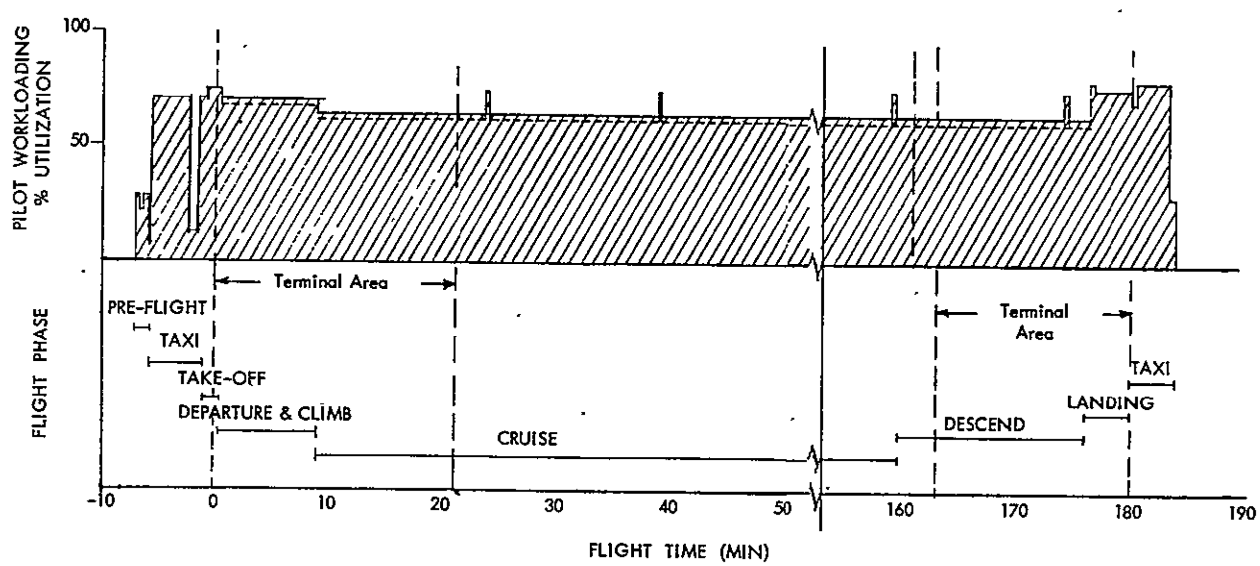


Figure 46 GA2 Pilot Workloading

6.2.2.1.4 GA2 Pilot

Figure 46 shows the general aviation pilot of limited financial means, that is with minimal comm/nav equipment, to be highly loaded throughout the enroute and the terminal phases of flight. The increase in workload is due in part to the lack of automatic flight control systems which could reduce control workload and permit the pilot to direct more of his attention to navigation of the aircraft, avoidance of hazards, and communications. The level of cockpit workload could also be reduced through use of an automated navigation and communication system.

Integration of the GA1 and GA2 pilot into the 1975-85 densely populated airspace will require extensive automation of the navigation, communication and control functions.

6.2.2.2 Communications Management Task

IFR/VFR air-to-ground and ground-to-air voice communications used by general aviation, air carrier, and military pilots have been catalogued by flight phase in Appendix D.

Typical message execution time for ground-to-air and air-to-ground contact are shown in Figures 47 and 48 respectively. These two bar charts also show the reduc-

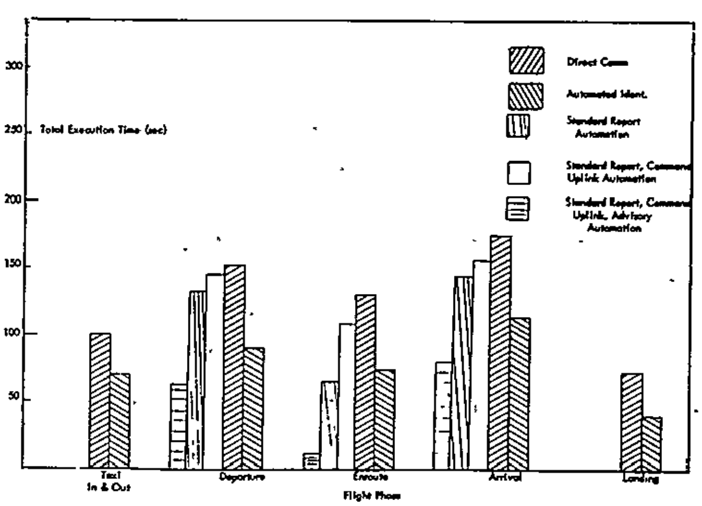


Figure 47. VFR Flight

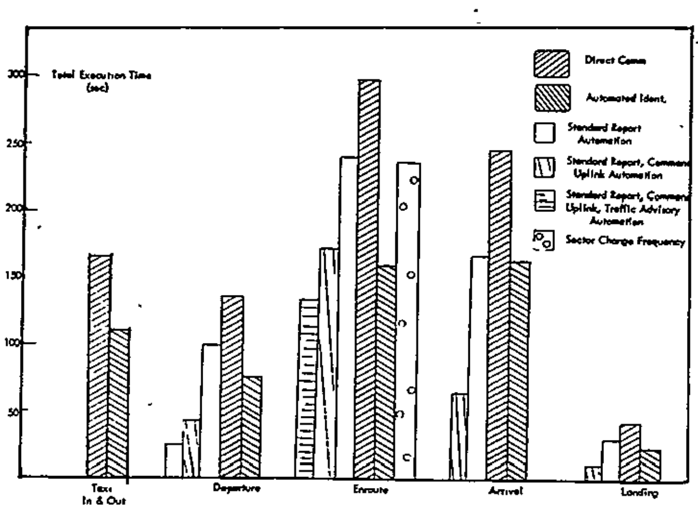


Figure 48. IFR Flight

Communications Workload

tion which could be achieved in pilot communication workload through automation of certain functions in the communications task.

6.2.2.2.1 Automation of VFR Communication

Enroute:

(1) Automation of the aircraft identification function through use of selective code calling could reduce workload by 40%.

(2) Automation of the aircraft position report function through use of an abbreviated data link report could reduce workload by 16%.

(3) Automation of the command data uplink function could reduce workload by 34%.

(4) Automation of the traffic advisory uplink function could reduce workload by 41%.

(5) Automation of the position report, the command data uplink, and advisory functions could reduce the enroute communication workload by 91%.

Terminal Area:

(1) Automation of the aircraft identification function through selective code calling could reduce workload by 38%.

(2) Automation of the position report function through an abbreviated data link report could reduce workload by 8%.

(3) Automation of the command data uplink function could reduce workload by 7%.

(4) Automation of the traffic advisory uplink function could reduce workload by 41%.

(5) Automation of the position report, the command data uplink, and advisory functions could reduce the terminal area communication workload by 56%.

6.2.2.2.2 Automation of IFR Communication

Enroute:

(1) Revision of the procedure requiring the aircraft to make a frequency change when entering a new sector to the requirement that the ground facility do the changing could reduce workload by 17%.

(2) Automation of the identification function through selective code calling could reduce workload by 40%.

(3) Automation of the position report function through an abbreviated data link can reduce workload by 17%.

(4) Automation of the command data uplink function can reduce workload by 20%.

(5) Automation of the traffic advisory uplink function could reduce workload by 11%.

(6) Automation of the position report, the command data uplink, and advisory functions could reduce the enroute IFR communication workload by 48%.

Terminal Area:

(1) Automation of the aircraft identification function through selective code calling could reduce workload by 37%.

(2) Automation of the position report function through an abbreviated data link report could reduce workload by 31%.

(3) Automation of the command data uplink function could reduce workload by 41%.

(4) Automation of the traffic advisory uplink function could reduce workload by 6%.

(5) Automation of the position report, the command data uplink

and advisory functions could reduce the enroute communication workload by 71%.

6.2.2.2.3 Automation of Communication

The automation of the position report function, command data function, and advisory function reduces the utilization of air-to-ground and ground-to-air voice link to a negligible level. The Flight Plan Reference concept results in minimal link usage in the enroute and terminal areas as a consequence of automation and and increased schedule reliability (e.g., better knowledge of actual time of arrival).

6.2.2.3 Navigation Management Task

All areas of pilot workload increased by the navigation management function can be reduced by onboard automation. The Flight Plan Reference concept employs an onboard computer. In the present system, the task of navigation management of the Moving Map Display (MMD) closely approximates the Flight Plan Reference system, since this system also uses an onboard computer with functions comparable to those of the Flight Plan Reference system. Percentage of operator utilization is as low as 29%, and a total management time of 73 seconds is required for a short haul mission.

In comparison, as shown in Table XXXIII, automation of the navigation function for INS, doppler, Loran C, Loran A, VOR/DME and the Course Line Computer can reduce navigation management workload from 492 seconds to the 73 seconds with the MMD, and thereby retain utilization of the operator at a constant level.

Also shown in Table XXXIII are pilot functions required to accommodate contingency flight conditions. The pilot workload graphs, Figures 38 through 46, do not show contingency/emergency conditions; however, such conditions as turbulence penetration, rerouting by ATC, clearance preparation, and radar identification are easily accommodated within workload limit by the pilot.

6.3 USER HARDWARE/CANDIDATE SYSTEM

The advanced navigation/traffic control systems discussed in Sections 4 and 5, although differing in detail, generally comply with the Flight Plan Reference ATC

TABLE XXXIII
NAVIGATION MANAGEMENT TASK SUMMARY

Minimum Automation Navigation Management Event	Task Time, sec. Ave.	Task Time, sec. Min.	% Utilization Pilot	% Utilization Navigator
In Flight Weather Evaluation	794	395	26.6	37.33
Inertial Navigation System Management	597	238	32.6	45.71
Doppler/Computer System Management	819	492	27.4	38.4
Loran A Manipulation	220	94	35.8	50.1
Loran C	265	255	26.3	36.8
Automatic Direction Finder	234	134	28.6	40.0
Fixing Radar	416	244	31.7	44.4
Weather Avoidance Radar	179	86	27.4	38.3
VOR/DME	245	139	26.5	37.1
CLC Management	194	117	23.9	33.5
Determination of Magnetic Course	146	72	33.4	47.5
Altitude Change Enroute	168	99	26.1	36.6
Monitoring Flight Plan Enroute (Fuel Management)	455	170	39.3	55.0
Copying and Acknowledging ATC Clearances (Oceanic)	124	59	28.6	40.0
Turbulence Penetration	17	9	19.4	27.9
Reroute by ATC During Enroute Phase	353	200	31.6	44.2
Radar Identification in Transition Zone	92	74	28.6	40.0
Altitude Change in Transition Zone	55	34	26.8	37.5
Navigation Management in Transition Zone	745	466	34.4	48.2
*Navigation Management of MMD	73	73	28.6	40.0

*No track monitor function

concept. In Section 5 it was stated that NAVSAT, GBTD, and PVOR/PDME systems can satisfy the navigation/traffic control system requirements of the 1975-1985 time frame. These area navigation systems were configured into airborne systems which appeared both feasible and practical for general aviation and air carrier users. Levels of automation by systems are compared to permit selection of a system which produces a minimum pilot workload.

In addition to fulfilling the pilot information needs listed in Table XXVI, the airborne system must provide ATC with surveillance information.

6.3.1 General Aviation - GA1, GA2.

The GA1 and GA2 aircraft navigation and communication management tasks should be minimized. GA1 and GA2 generally fly at altitudes below 11,000 ft, which is the altitude regime of the terminal area. Pilot utilization related to the basic task of flying the aircraft accounts for 60% utilization of the pilot. Automation can provide the GA1 and GA2 pilot with significant improvements in performance at no increase in workload, a necessary condition to his continued operation in the terminal area of 1975-85. Two cases are discussed:

(1) VFR uncongested, uncontrolled airspace. -- It was determined that the minimum navigation requirement is for a range and bearing to a desired location; e.g., city, landmark, airstrip, air terminal, etc.

(2) VFR congested, controlled airspace. -- The Flight Plan Reference system is utilized.

The primary information needs of the GA1 and GA2 pilot are: track angle error and distance-to-go to a known point. The corresponding flight plan needs are: ETA, speed, and cross track deviation. Position information is ordered into three priorities. The first priority is range and bearing; the second is northings and eastings; and the third is latitude and longitude. All of the systems are organized to comply with the information need and the first priority position.

6.3.1.1 System Levels of Automation

6.3.1.1.1 Candidate Systems

The candidate general aviation GA1, GA2 navigation systems are shown in Tab. XXXIV. Navigational Satellite, Ground Based Time Difference, and PVOR/PDME were selected as candidate navigation systems. NAVSAT ephemeris data is supplied to assist the pilot in the use of the NAVSAT system. Since GA1 and GA2 flights are made under VFR flight plan conditions, it was assumed that standard aeronautical charts would be retained as reference material. Charts for use with PVOR/PDME and NAVSAT systems

TABLE XXXIV
GENERAL AVIATION (GA1, GA2) ADVANCED NAVIGATION/TRAFFIC CONTROL SYSTEMS

USER	General Aviation System - Levels Of Automation	NAVIGATION: UHF (VOR) NAV/COMM Receiver	NAVIGATION: UHF DME NAV Rec.	NAVIGATION: UHF NAV SAT Rec. - Manual Acq.	NAVIGATION: UHF NAV SAT Rec. - Auto Acq.	NAVIGATION: LF Ground Based TD Rec. - Manual Acq.	NAVIGATION: LF Ground Based TD Rec. - Auto Acq.	NAVIGATION: NAV SAT Ephemeris Data Tables	MAPS: Local Aeronautical Chart	MAPS: Local Aeronautical Chart - GB TD Contours	COMPUTERS: Hand Held DR Computation Aid	COMPUTERS: DR AT/CT Computer	COMPUTERS: GB TD Computer	COMPUTERS: Course Line Computer	COMMUNICATION: VHF Voice Link	COMMUNICATION: VHF Data Link - Min.	COMMUNICATION: VHF Data Link - Max.	GROUND SYSTEM: NAV SAT PF and Guidance, DR	GROUND SYSTEM: GB TD PF and Guidance, DR	GROUND SYSTEM: Storeable Flight Plan
GA1, GA2	g1			x				x	x		x				x			x		
GA1, GA2	g2				x			x	x		x				x			x		
GA1, GA2	g3					x				x	x				x				x	
GA1, GA2	g4						x			x	x				x				x	
GA1, GA2	g5				x			x	x		x				x			x		x
GA1, GA2	g6						x			x	x				x				x	x
GA2	g7				x			x	x		x				o	x		x		x
GA2	g8						x			x	x				o	x			x	x
GA2	g9				x				x			x			x	x		x		x
GA2	g10				x				x			x			o		x	x		x
GA2	g11						x			x			x		x	o				x
GA2	g12						x			x			x		o		x			x
GA2	g13	x	x						x						x					x
GA2	g14	x	x						x					x	o		x			x

x: Also used with navigation units g1, g2, g5 and g7
o: Voice as backup

will be utilized; aeronautical charts which portray time difference contours would be used with the GBTD system. Computers assumed to be available to the general aviation pilot were the standard hand-held computation aid, such as the E6B, Jeppesen MB-4, etc., a dead reckoning along track/cross track computer, a GBTD computer, and/or a course line computer. The communication link was assumed to be either direct voice, a minimum data link, or a full capability data link. These are defined as the airborne system components.

The ground-based elements of the NAVTRACS system provide system assistance to the general aviation pilot by processing the received and retransmitted NAVSAT and GB Time Difference information; thereafter returning to the aircraft position fix, guidance and dead reckoning information. The flight plan reference ground store is required for implementation of a VFR controlled airspace system.

Table XXXIV identifies the 14 candidate general aviation systems. Each system is designated by a descriptor: g1, g2, ...g14, which is carried throughout the following discussion. Systems g1 . . . . g8 are candidates for GA1. Systems g1 . . . . .g14 are candidates for GA2.

The candidate systems g1 . . . g14 are organized to represent different levels of system automation. As the degree of automation of the baseline systems g1 (NAV SAT), g3 (GBTD), and g11 (rho-theta) is increased (g2, g4 . . . g14), the trade off in pilot workload can be evaluated. The system benefit per workload reduction is then assessed for the <u>incremental</u> increase in automation.

6.3.1.1.2 GA1, GA2 Surveillance Systems

Table XXXV identifies the surveillance and control links to the ATC unit for the general aviation aircraft. The communications loop for the GA user of the NAV SAT or GBTD candidates may utilize a voice link, an UHF minimum capacity data link or a full capacity data link. The minimum data link, as will be shown, down-links encoded time difference information to the ground system. The uplink is used to provide aircraft fix or guidance information.

TABLE XXXV
GENERAL AVIATION (GA1, GA2) SURVEILLANCE SYSTEM

System Identification	Primary NAV System	Primary Surveillance Link (A-G)	Backup Ground System Link	Surveillance Function: Terminal Area	Surveillance Function: Enroute (Full Report)	Command Function: Link (G-A)
		ATC Surveillance Interrogation	Mandatory/Standard Report			
g1, g2	NAV SAT	voice	voice	voice	voice	UHF voice
g7	NAV SAT	*UHF min data link	voice	*UHF min data link	voice	UHF data link
g9	NAV SAT	UHF min data link	voice	min data link	voice	voice
g10	NAV SAT	full data link	full data link	data link	data link	UHF data link
g3, g4, g6	GBTD	voice	voice	voice	voice	voice
g8	GBTD	VHF min data link	voice	VHF min data link	voice	VHF min data link
g11	GBTD	voice	voice	VHF min data link	voice	voice
g12	GBTD	full data link	full data link	data link	data link	data link
g13	VOR/DME/ CLC	voice	voice	voice	voice	voice
g14	ρ/θ/CLC	full data link	full data link	data link	data link	data link

*not real time surveillance: delay to max [13 sec, $U_{NI}(11 \times 10^{-3})$ sec]. SSR = 6 sec to 18 sec information delay.

TABLE XXXVI
GENERAL AVIATION (GA1, GA2) PRIMARY METHOD OF SYSTEM USE

System Ident.	Primary NAV System	Flight Phase – VMC: Taxi	Take Off	Departure-Climb Out	Enroute Uncontrolled Area	Enroute Controlled Area	Arrival – Approach	Final Approach	Landing
g1, g2, g5, g7	NAV SAT	visual	runway mag. heading	map, pilotage, mag. heading	map, pilotage, fix vector to reference	map, pilotage, NAV SAT, way point	map, NAV SAT, insert way point	visual	visual
g3, g4 g6, g8	GB TD	visual	runway mag. heading	map, pilotage, mag. heading	map, pilotage, fix vector to reference	map, pilotage, GB TD, way point	map, NAV SAT, insert way point, GB TD, insert way point	visual	visual
g9, g10	NAV SAT	visual	runway mag. heading	map, pilotage, air data DR, way point insert	map, pilotage, air data DR, way point insert	map, NAV SAT, air data DR, way point insert	map, NAV SAT, air data DR, insert way point	visual*	visual
g11, g12	GB TD	visual	runway mag. heading	map, pilotage, way point insert	map, pilotage, way point insert	map, GB TD, way point insert	map, GB TD, way point insert	visual*	visual
g13, g14	VOR/DME CLC	visual	runway mag. heading	map, pilotage, way point insert	map, pilotage, way point insert	map, VOR/ DME CLC, way point insert	map, VOR/ DME CLC, way point insert	visual**	visual

Systems g1 thru g14 GA2: IFR, VFR controlled airspace, VFR uncontrolled airspace.
Systems g1 thru g6 GA1: VFR uncontrolled airspace, VFR controlled airspace.

*GA2 can use system on final approach in reduced VMC.
**GA2 can use system on final approach with LOC mode.

The communications loop employed with VOR/DME systems does not include a full capacity link.

6.3.1.1.3 Primary Method of System Use

Table XXXVI shows the principal method used by the pilot to guide the aircraft throughout the flight profile. During taxi, take off, final approach and landing, the pilot utilizes visual guidance. During the enroute phase of flight, the techniques utilized by the pilot vary according to whether the flight is conducted in VFR uncontrolled airspace or VFR controlled airspace. Table XXXVI again shows the specifics of the situation.

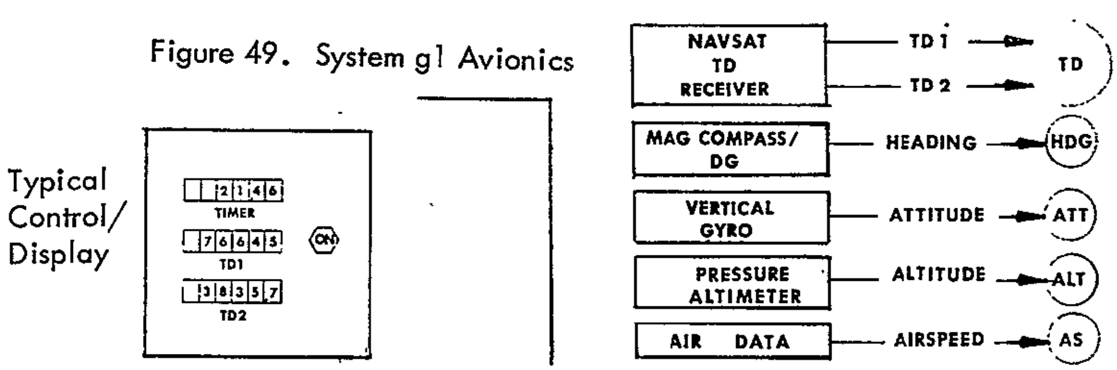
The general Event Sequence Diagrams presented in Appendix A have been applied to these specific systems g1 . . . g14. The use of each candidate system is summarized in Appendix H. The resultant task listing, times and related percentage of pilot utilization values are tabulated in this Appendix as well.

Several of the systems are designed to link TD information to the ground where aircraft position is computed. Subsequently, range and bearing to waypoint is uplinked to the aircraft. Appendix H shows the related algorithm and operational sequence diagram.

6.3.1.1.4 GA1, GA2 System g1

The principal position information provided by the g1 system to the pilot is NAV SAT time difference information. The pilot utilizes standard flight instruments: magnetic compass, altimeter, altitude indicator, and indicated airspeed meter. (See Figure 49). The receiver requires manual search and acquisition of the TD signals. The

Figure 49. System g1 Avionics



pilot refers to a navigation chart as his cueing device. When desiring a fix, the pilot locates his DR position on the chart, consults NAV SAT ephemeris tables, aligns the receiver, and initiates contact with the ATC center. Through voice communication, the pilot links the position estimate, the coded waypoint destination, time of fix, TD1, TD2, altitude, true airspeed and heading. The ground system, with NAV SAT ephemeris stored, computes and uplinks on direct communication the range and magnetic course to the coded waypoint. The pilot then manually performs the remaining navigation management tasks of updating the steering, checking flight path status, and checking flight plan status. Figure 50, shows the ground function. The detailed procedure and control display panel is shown in Appendix A. The effects of user saturation are discussed in Appendix F, Section F.4.3.

6.3.1.1.5 GA1, GA2, System g2

System g2 is identical to g1 except that this NAVSAT receiver employs automated search and acquisition.

6.3.1.1.6 GA1, GA2 System g3

The information output to the pilot is GBTD time difference information. The ground system stores the GBTD transmitter locations. Otherwise the system is used in a fashion identical to that used in System g1.

6.3.1.1.7 GA1, GA2 System g4

The GBTD receiver of System g4 is equipped with automatic search and acquisition of the time difference signals. The system is used in the same manner as System g3.

6.3.1.1.8 GA1, GA2, Systems g5, g6

These systems employ the flight plan reference ATC concept. The g5 airborne

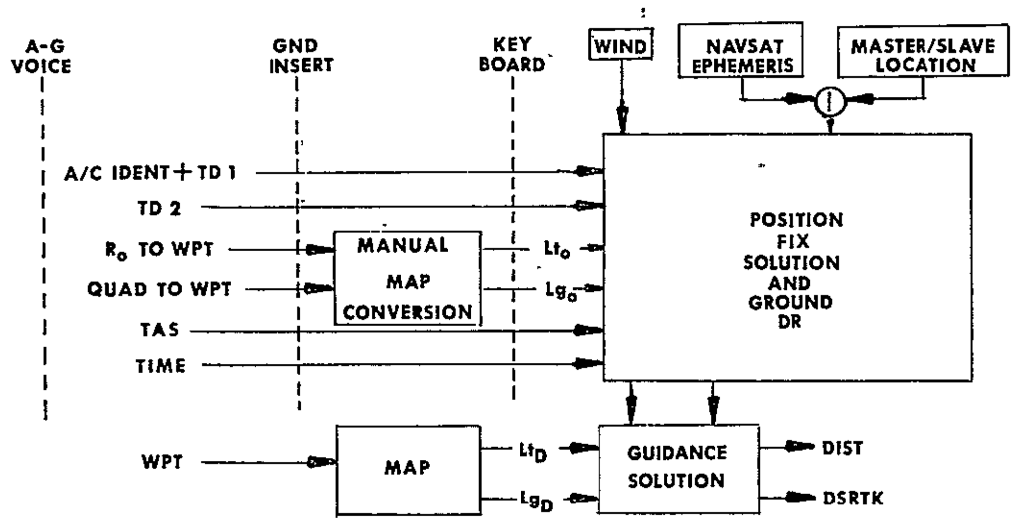


Figure 50. System g1 Ground Complement

system is identical to the NAVSAT g2 concept. The g6 airborne system is identical to the GBTD g4 concept. Receiver automatic search, acquisition and track is mandatory. The ground system, which has access to NAVSAT ephemeris or the GBTD chain locations, uses the flight plan reference system to increase surveillance and minimize the volume of messages. Down-link voice data include: time, TD1, TD2. Uplink voice data, computed from current aircraft leg, are: distance to go and desired track. Figure 51 shows the ground system.

Appendix H contains the operational sequence diagram describing the process by which vehicle position is determined.

6.3.1.1.9 GA2 Systems g7, g8

Systems g7 and g8 are identical to Systems g6 and g7, but a minimum-capacity data link is added to the systems. The voice communication down-link is eliminated as the primary link for position fix data. The minimum capacity data link automatically provides surveillance data to the ground upon demand of the ATC system ; if the pilot desires a fix a request is down-linked to the ground.

Figures 52 and 53 show the airborne and ground systems respectively.

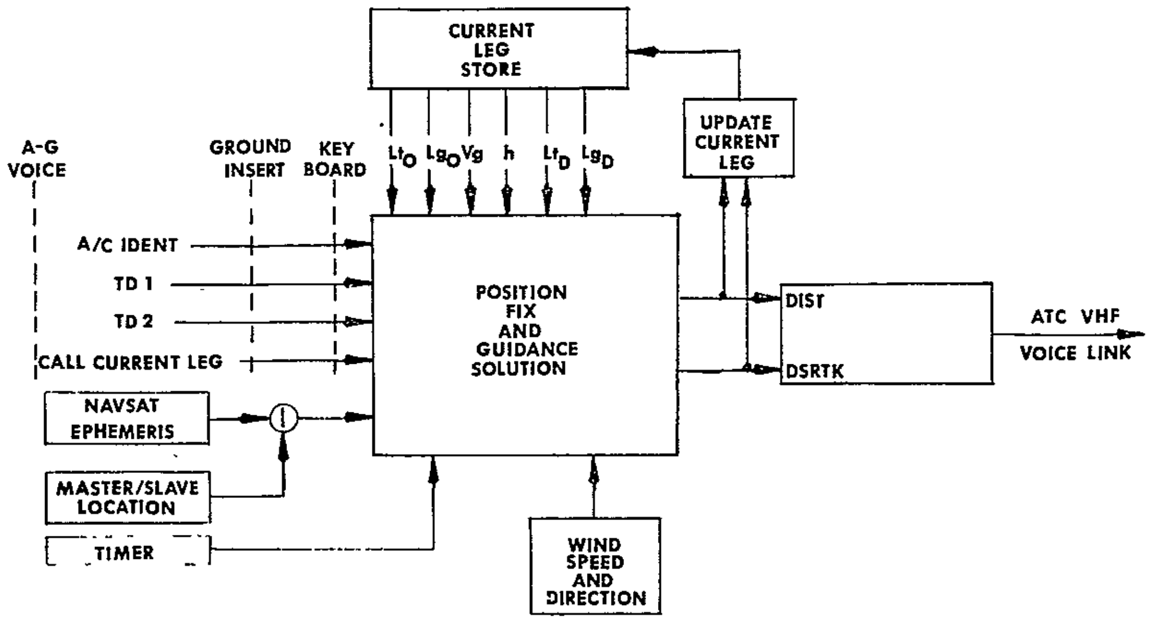
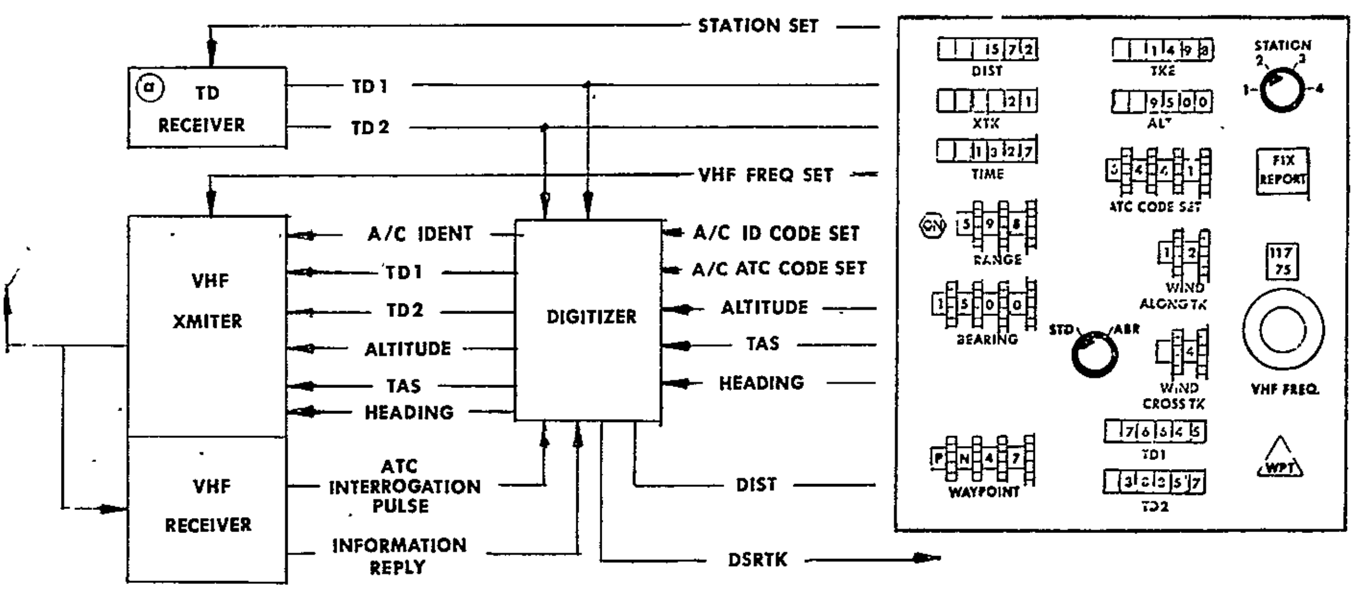


Figure 51. Systems g5, g6 Ground Complement



ⓐ GROUND BASED DIFFERENTIAL TIME DIFFERENCE OR NAVSAT RECEIVER

Typical Control/Display

Figure 52. Systems g7, g8 Avionics

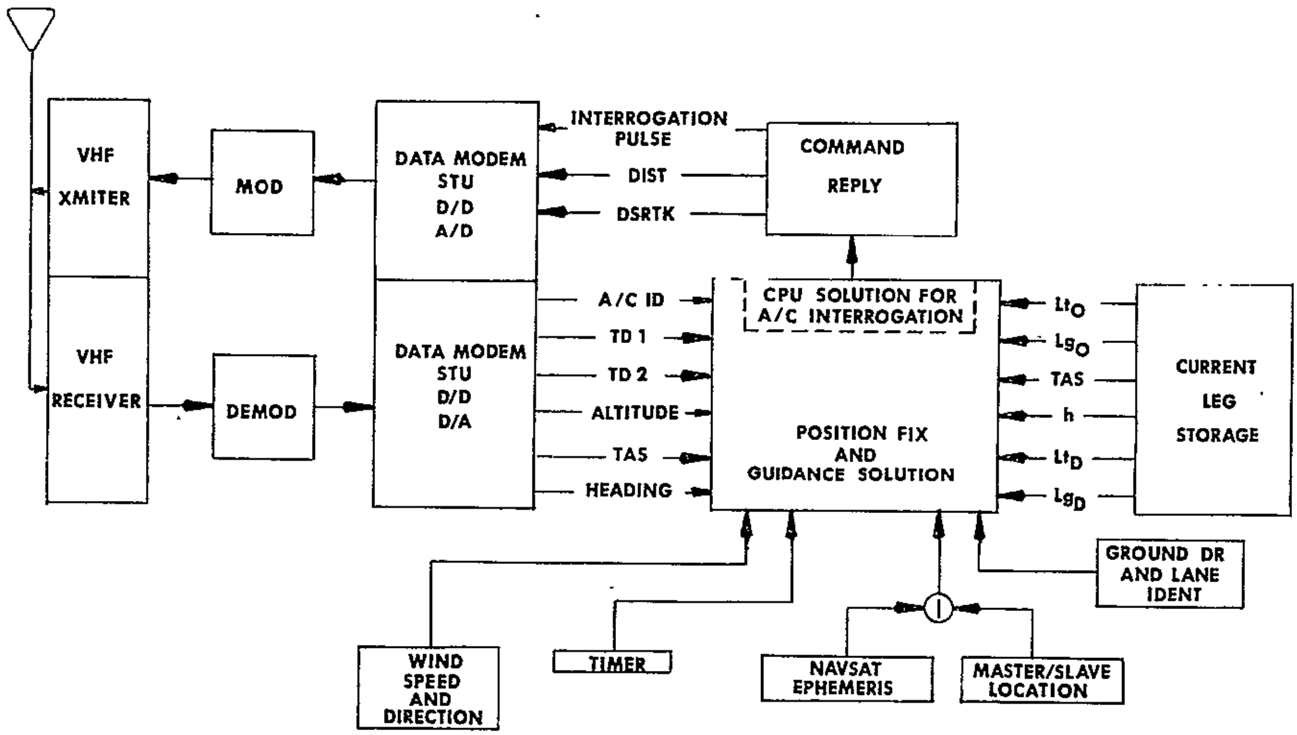


Figure 53. Systems g7, g8 Ground Complement

6.3.1.1.10 GA2 System g9

System g9 provides for the addition of an along track/cross track computer to the basic NAV SAT configuration of g7. The use of a DR computer provides three primary benefits: it makes possible the provision of continuous surveillance information to the ground facility if required; it continuously provides the pilot with real time information about his relative position; and it protects the pilot from the possibility of loss of position information in the eventuality that the NAV SAT system is momentarily saturated (Appendix F). The System is assumed to have access to magnetic compass, air data and wind inputs.

6.3.1.1.11 GA2 System g10

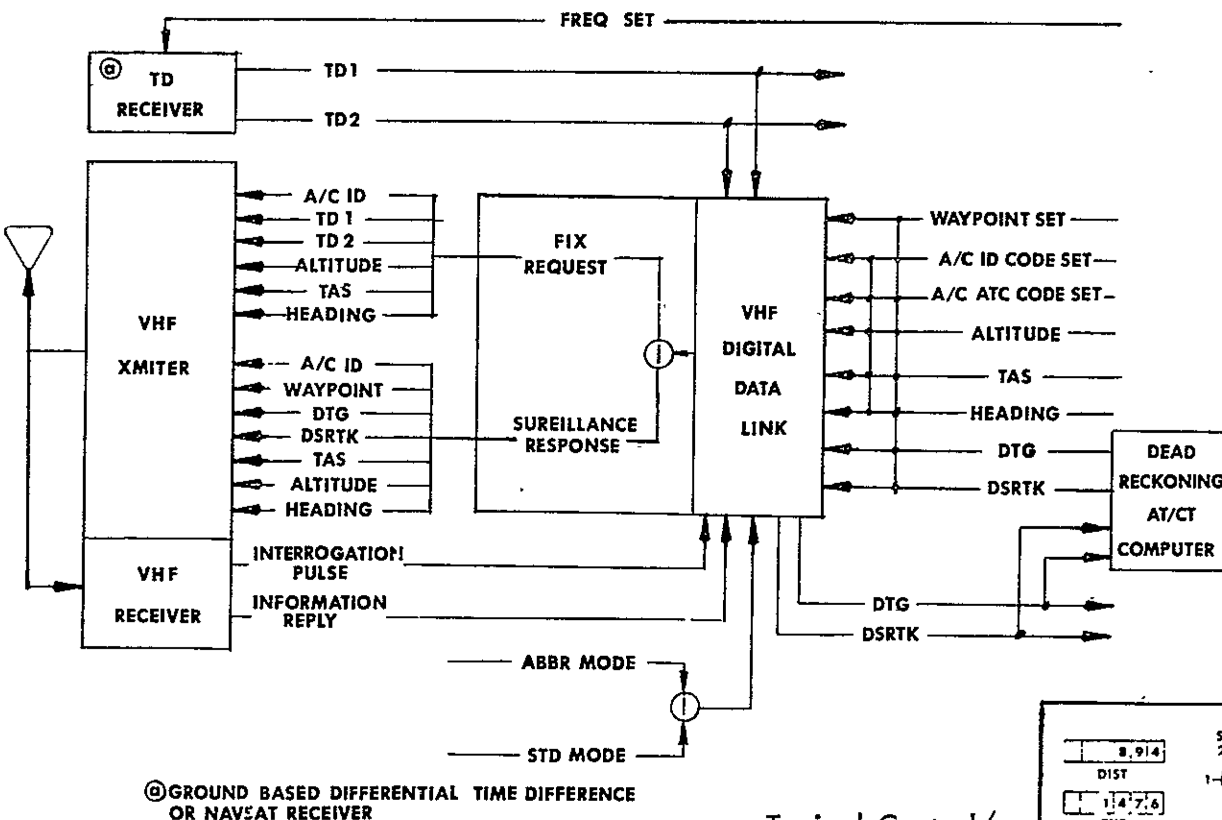
A full digital data link is added to the components of System g9 to create

System g10. These elements include a NAV SAT time difference receiver with automatic search and track capability and an along track/cross track DR computer. The ground system utilizes the complete Flight Plan Reference concept.

Figure 54 illustrates the airborne system. The fix request mode dumps TD1, TD2, altitude, true airspeed and heading to the ground. The response to an ATC surveillance request generates a standard report.

6.3.1.1.12 GA2 Systems g11, g12

These Systems contain a GBTD receiver and integral coordinate converter. The g11 System is independent of the ground system, but supplies surveillance data upon demand from the ground through use of minimum link. Appendix H sizes the coor-



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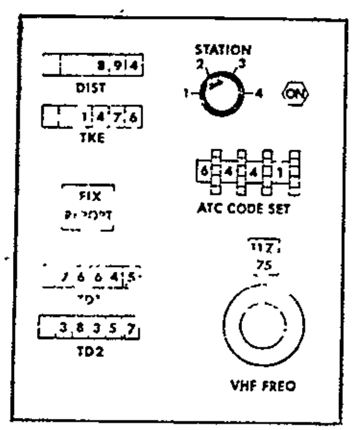
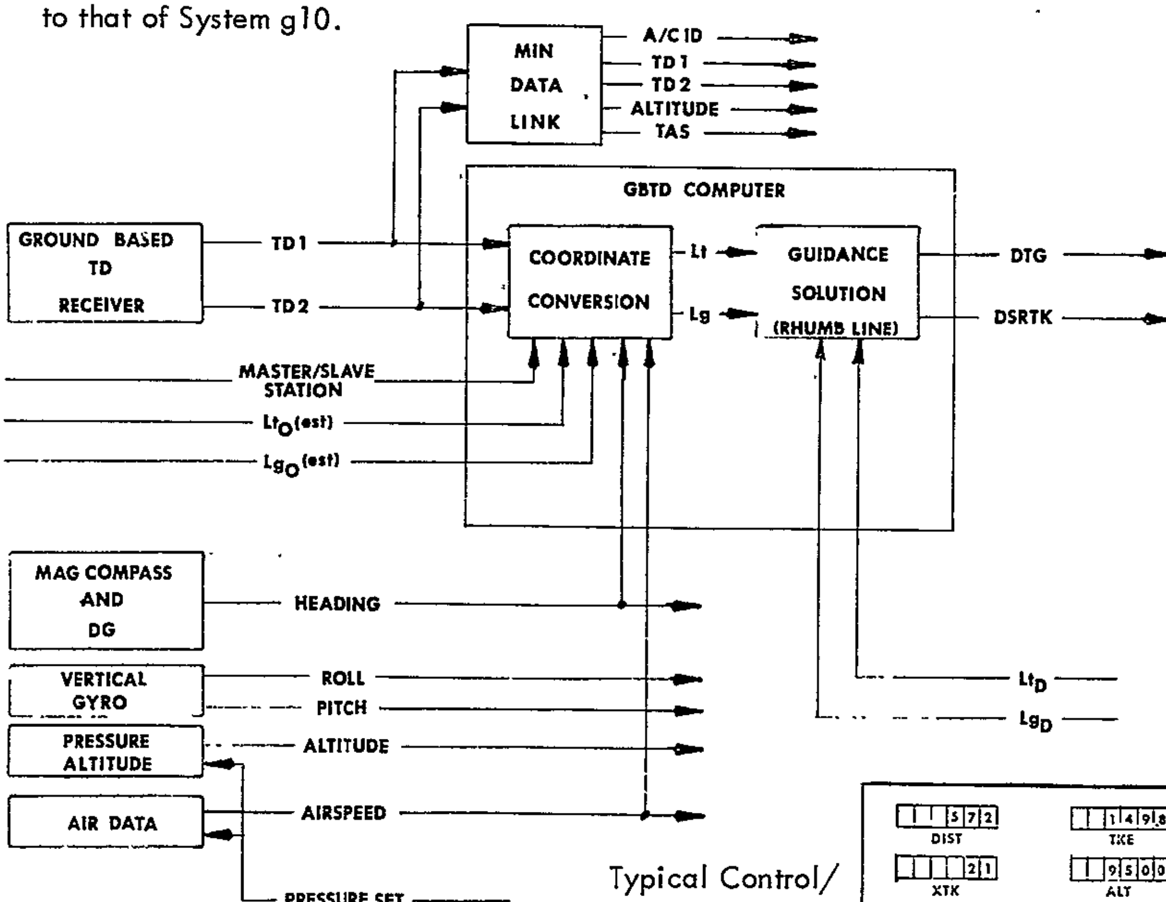


Figure 54. System g10 Avionics

dinate conversion and guidance solution for a general aviation aircraft. The complete solution permits continuous surveillance data to be available and minimizes the need for a dead reckoning capability. Operation is comparable to System g4. (See Figure 55.)

System g12 augments g11 with a full data link. This data link is identical to that of System g10.



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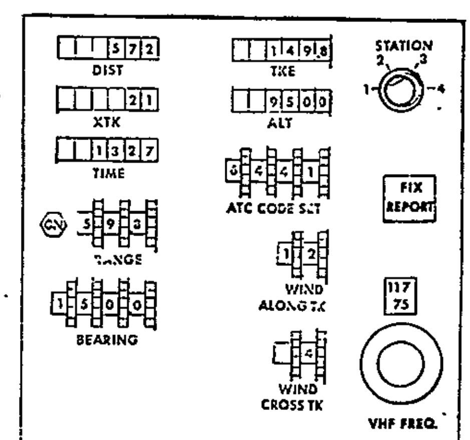
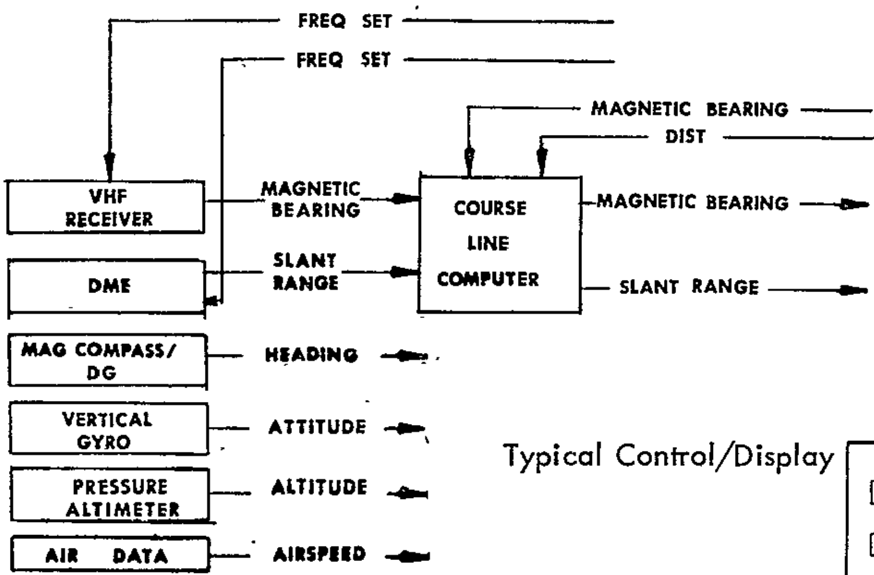


Figure 55. System g11 Avionics

6.3.1.1.13 GA2, Systems g13, g14

The rho/theta System g13 does not use a course line computer. This system is introduced solely for purposes of comparison. System g14 utilizes a course line computer and a data link.

Figure 56 shows the airborne avionics system.



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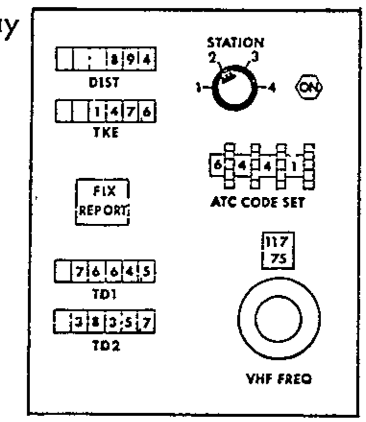

Figure 56. System g 14 Avionics

6.3.1.2 GA1, GA2 Pilot Workload

As shown in Figure 46, back in Section 6.2, the general aviation pilot is significantly loaded throughout all phases of flight. Therefore, the navigation management tasks required of the GA1, GA2 pilot should be minimal. Systems g7 and g8 provide maximum flexibility to the GA1 pilot. Systems g9 . . . g14 provide maximum flexibility and minimum workload to the GA2 pilot.

The pertinent navigation management tasks of the GA1 and GA2 pilot can be characterized basically as that of inflight system reprogram. The pilot must be able to quickly reprogram the navigation system, and, in a short time, to acquire his new steering signal.

Contingency information received from any one of the sources of advisory information or the detection of conditions hazardous to flight can initiate a need to modify the flight path and thus to necessitate a change in the stored flight plan system. Changes in the stored plan can occur anywhere during enroute or terminal area flight, in response to a traffic control vector input, or in response to a command to initiate a holding maneuver.

Figure 57 shows the pattern of pilot workloading experienced during the performance of the tasks of flight plan modification and steering data acquisition. This workload is characteristic of the terminal area. For the GA1 user, Systems g7 and g8 are the alternative solutions. For the GA2 user, Systems g10 . . . g14 minimize workload.

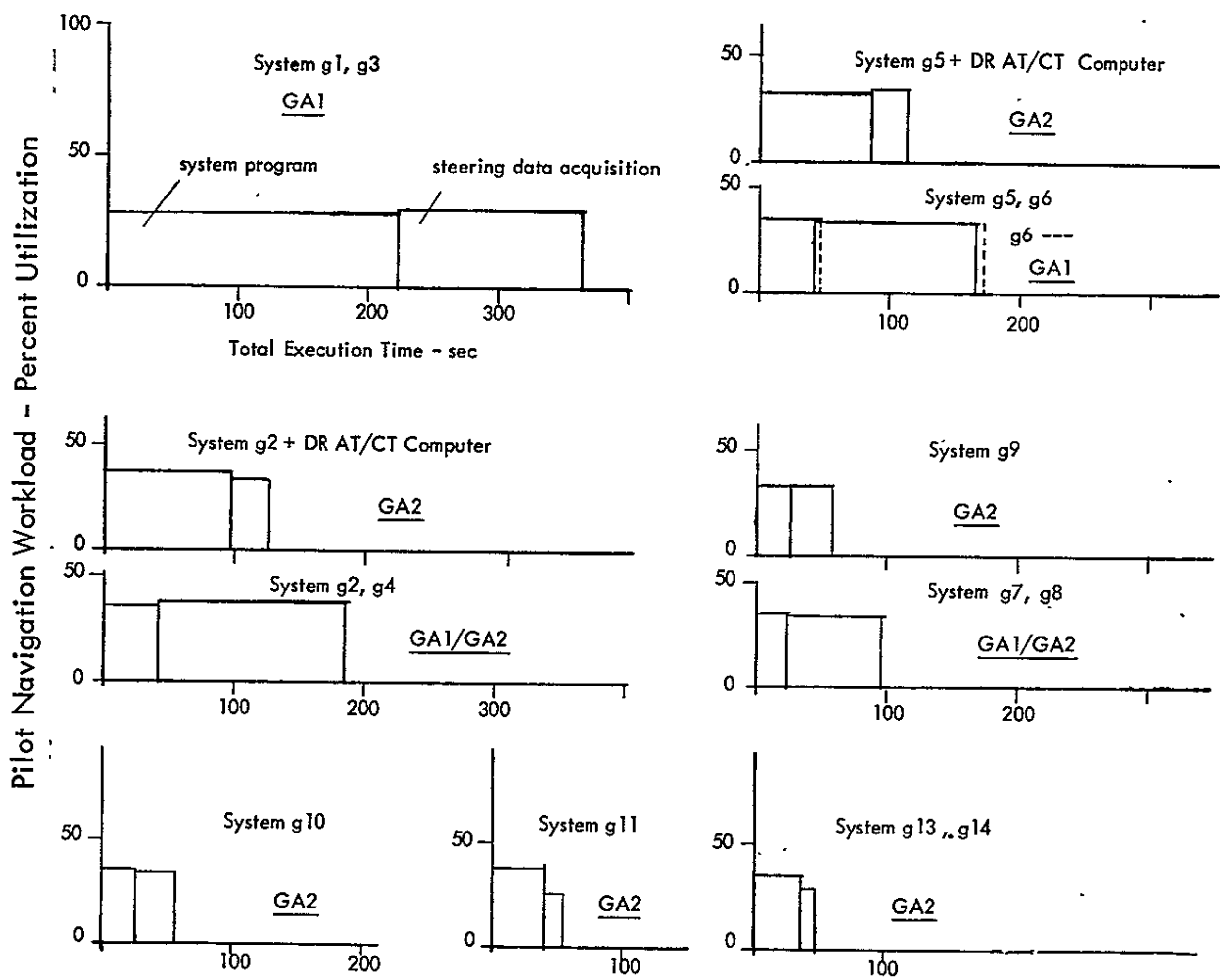

Figure 57. General Aviation (GA1, GA2) Pilot Navigation Management Workload

Task times and percent utilization of the pilot expected for operation in the terminal area are shown in the following Figures 58 and 59. The level of activity in the terminal area is the principal motivational factor in suggesting use of the flight plan reference system. When the specified level of system automation is provided, it is found that: (1) pilot workload is held relatively constant; and (2) task complexity is related to task duration.

The GA1, GA2 aircraft tend to cruise at the altitudes which come within the terminal area altitude envelope. Thus, on many cross-country flights, the GA pilot finds himself faced with terminal area workload though he is actually operating on the enroute portion of his flight plan. During this period, the inherent workload should be reduced and no additional burden placed on the pilot by the ATC Flight Plan Reference System. Systems g7 . . . g14 were evaluated for pilot workload during a typical enroute leg.

6.3.1.2.2 Enroute Workload

The typical navigation management tasks performed by the GA1, GA2 pilot during the enroute portion of his flight includes review of the current weather forecast; frequent reviews and verification of system status and performance; obtaining position measurement data with which to determine navigational error and to generate steering signals; perform flight plan check; and prepare and deliver ATC required position reports. On occasion the weather report may be updated or revised, resulting in a re-evaluation of fuel requirements and ETA.

Figures 58 and 59 show the navigation management workload imposed upon the general aviation pilot. It is assumed in these workload assessments that the GA1 pilot utilized systems g7 or g8, and that the GA2 pilot utilized one of the systems g9 . . . g14. With these systems, the acquisition of position and steering data required a minimum of both the pilot's time and effort, and the remaining navigation management tasks result in a relatively constant level of percentage of pilot utilization.

The general aviation pilot workload is significantly reduced if provision is made in the airborne system for automatic flight plan status checks. Storable flight plans and minor computational aids reduce pilot workload appreciably. The time required to perform the flight plan status check for the GA1 pilot is 28% (g7, g8) of total leg management time. The GA2 pilot (g9 . . . g14) utilizes 30% to 56% of the navigation management time in performing the flight plan status check. Of those systems which offer minimum

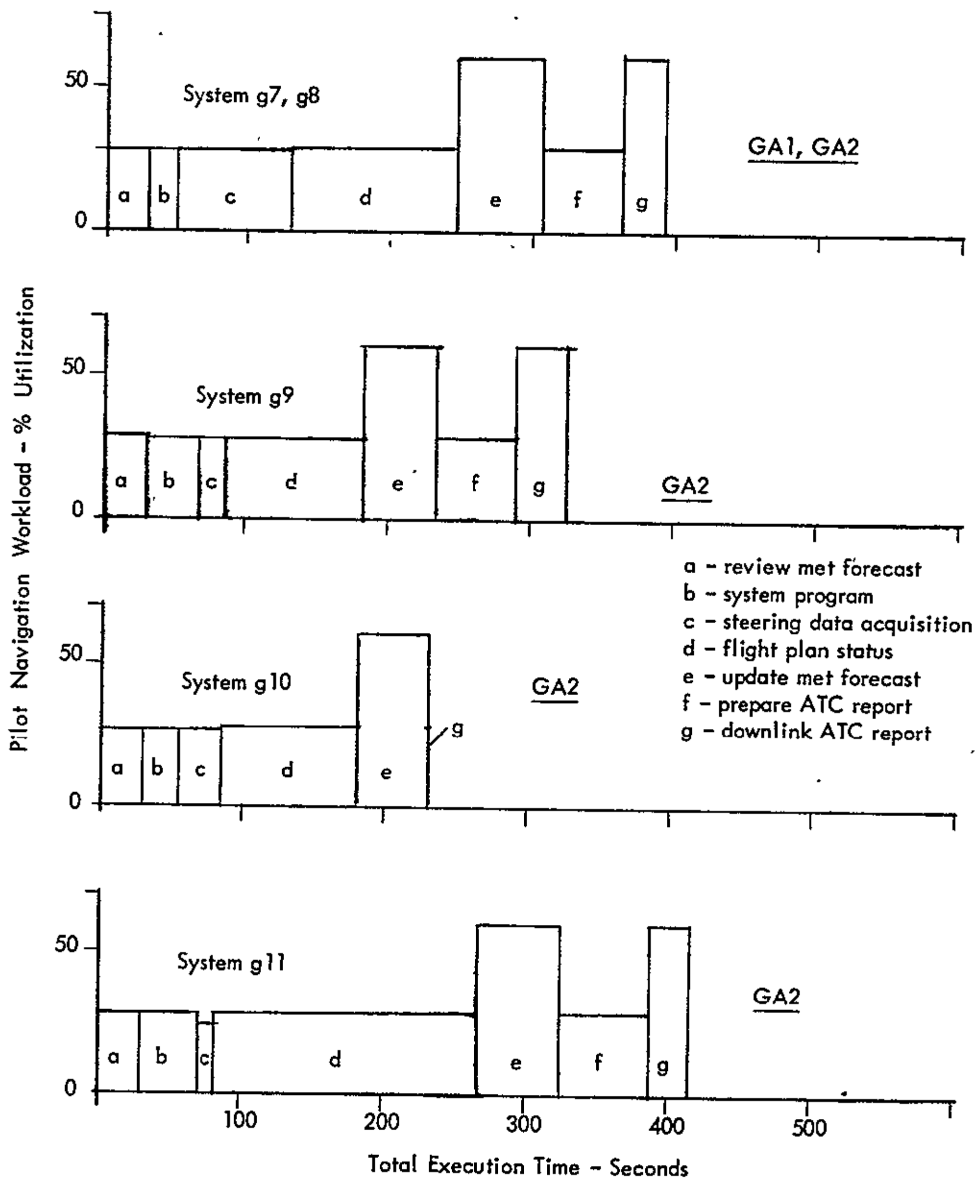

Figure 58. General Aviation (GA1, GA2) Pilot Navigation Management Workload

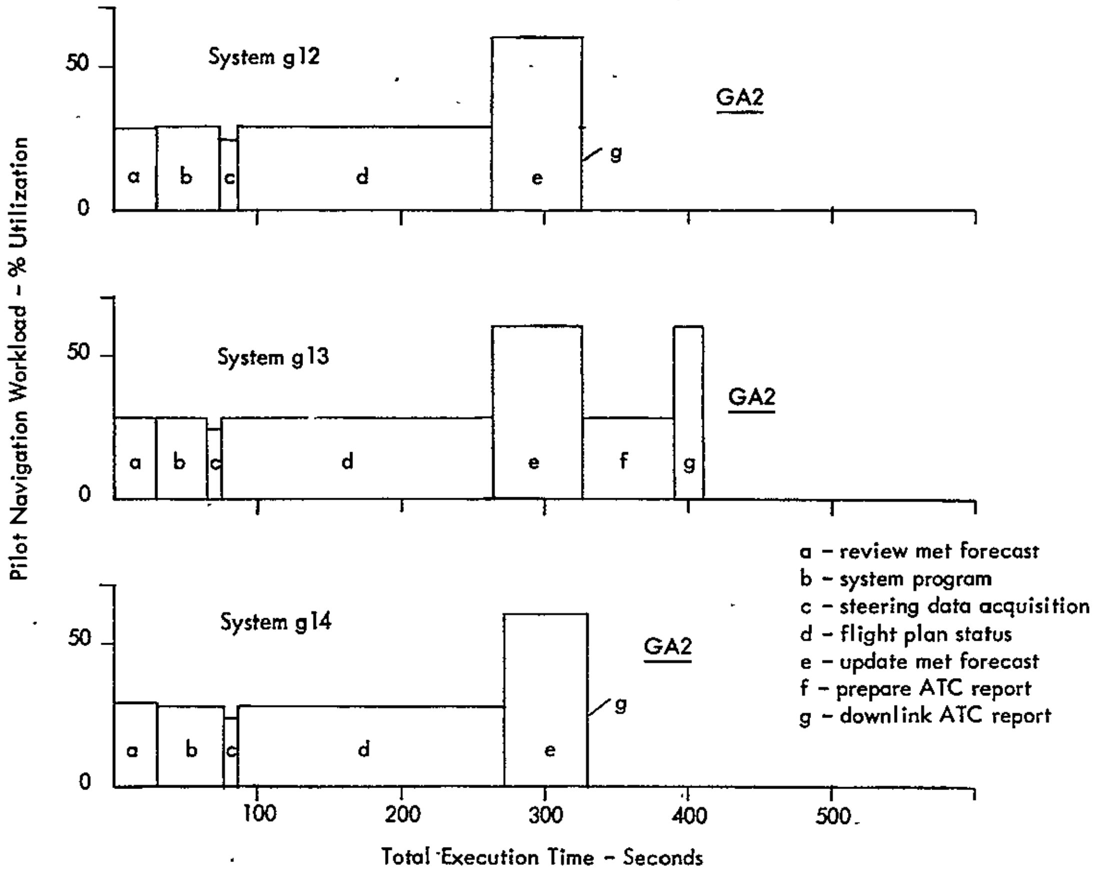

Figure 59. General Aviation (GA1, GA2) Pilot Navigation Management Workload

execution time - systems g10, g12 and g14 - the greatest potential reduction in remaining execution time would occur from automation of the flight plan status check. Time consumed could be decreased by as much as 56%.

Systems g7 and g8 do load the GA1 pilot, but with proper training and experience the operation of the systems remain within the capacity of the pilot. Systems g10, g12 and g14 indicate greatest promise for the GA2 pilot's use.

6.3.1.2.3 Total Mission Pilot Workload

Generally, as shown in Figures 57 through 59, the percentage of pilot utilization is relatively constant; however, elapsed time consumed in the performance of navigation management tasks does vary. Because of this apparently constant level of pilot utilization time, especially during the GA2 mission, the parameter which was used to evaluate the system benefit was total execution time. The nominal mission selected for evaluation is typified by the 525 nmi GA2 flight defined in Section 2. Each of the candidate navigation systems was exercised in accordance with the functions and tasks outlined in the navigation management event sequence diagram described in Appendix A. Navigation and communication management functions related to VFR operations were exercised in a similar way with respect to the VFR Flight Plan controlled airspace Event Sequence Diagram. The results of these efforts are shown in Figures 60, 61 and 62.

Figure 60 shows that navigation management workload in the Terminal area for the departure/climb out and arrival/descent phases is relatively constant when the NAV SAT and GBTD, g7 and g8 systems of GA1 are used. The GA2 pilot was assumed to have access to a greater level of navigation system automation; thus a 30% to 50%

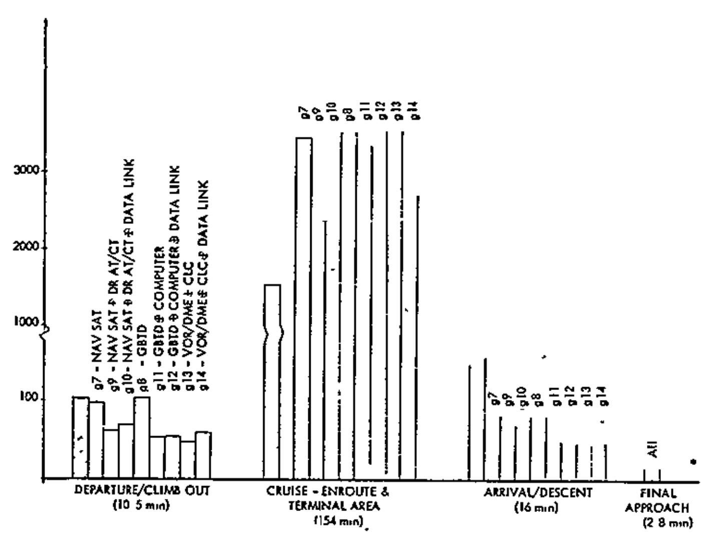

Figure 60. General Aviation (GA1, GA2) Navigation Management Workload Summary

workload reduction can be achieved for terminal area operations with systems g9 . . . g14. Furthermore, equipments g11 . . . g14 reduce the navigation management total task execution time by 30% as compared with the measurements obtained for g9 and G10.

Measurements performed during the study indicate that workload experienced during the cruise phase of flight can be reduced by 50% for the GA2 pilot through use of system g10 as contrasted with the GA1 pilot, and by 25% as compared with the g9 system. Furthermore, the use of systems g12 and g14 during the enroute portion of the flight indicated a possible reduction of total execution time of 25%.

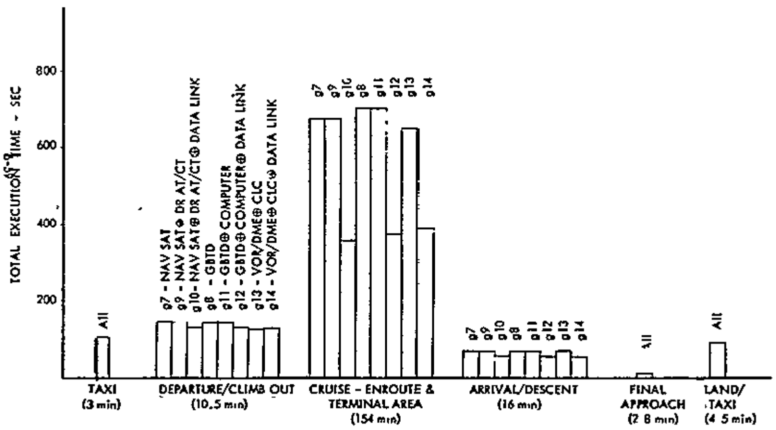

Figure 61. General Aviation (GA1, GA2) Communication Workload Summary

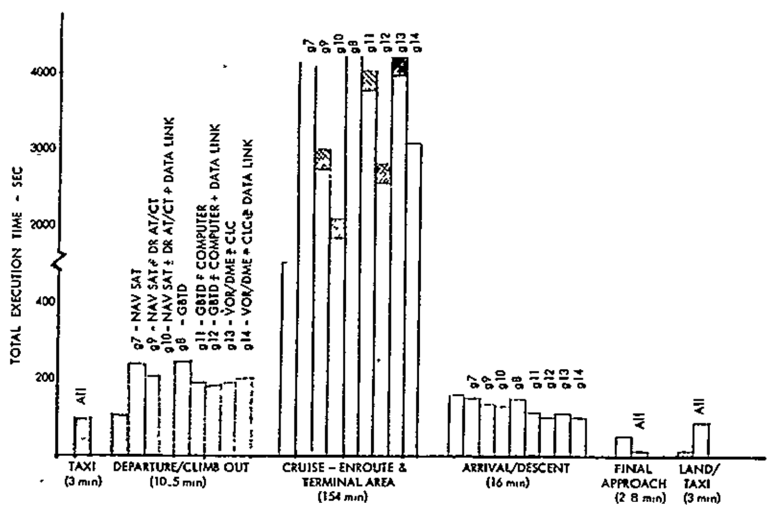

Figure 62. General Aviation (GA1, GA2) Navigation Management and Communication Management Workolad Summary

Use of a full data link streamlines the communication management task significantly, as shown in Figure 61. The data link can reduce time required for communications during the enroute portion of the flight by as much as 42%. In the departure and arrival terminal area where the primary communication task is that related to surveillance, the total execution time remains approximately constant for both users regardless of equipment employed, e.g. GA1 and GA2, and systems g7 . . . g14.

The total navigation and communication management tasks are summarized in Figure 62. The total execution time shown requires approximately 60% utilization of pilot capacity.

The fully automated candidates, systems g10, g12 and g14, provide workload reductions during enroute operations of 50%, 33% and 26%, respectively. The workload analysis for the departure and arrival terminal area indicated that all systems require a comparable amount of attention by the pilot; however, systems g11 . . . g14 do provide for a reduction in total execution time of 30%.

System concepts g7 . . . g14 are capable of meeting the general aviation operational requirement of the 1975-1985 time period. Of the systems described above, g7 and g8 systems meet the requirements of the GA1 pilot; systems g10, g12 and g14 provide a greater reduction to GA2 pilot workload than do systems g9, g11 and g13; however, regardless of system used the pilot can meet system performance requirements. In summary, it was determined that the GA1 and GA2 pilot would be able to successfully manage all aspects of his flight: e.g., to adhere to the Flight Plan Reference system; to have freedom of route selection; and to supply, whenever required, the surveillance data to ATC.

6.3.1.2.4 Workload Reduction - Moving Map Display

The GA1 and GA2 pilot regularly refers to the aeronautical chart for flight planning, for inflight position fixing and to verify position with respect to flight plan, to locate essential aeronautical data and to determine minimum safe altitude, etc. An

improvement in the workload situation could be obtained by using a moving map display. The principal function of the suggested GA instrument would be to display aircraft position on an aeronautical chart. Because the driving input to the display must come from an onboard computer, the systems which interface most readily with a MMD are the NAV SAT system g10; the GBTD system g12; and the VOR/DME CLC system, g14. It is estimated that the use of the moving map display could reduce pilot workload of these configurations by 8 to 10% (see Figure 62) on the basis of the pilot utilization evaluation performed in this study.

6.3.2 Air Carrier Users and GA3

It was assumed that the typical air carrier and GA3 aircraft would make extensive use of onboard general purpose computers, data link, and one or more of the NAV SAT, GBTD area navigation systems, PVOR/PDME, GBTD and/or NAV SAT. Table XXXVII defines the air carrier and GA3 system levels of automation. Each system is identified with a descriptor v1, v2 . . . v10; this form of designation is used throughout the following discussion.

The primary navigation system, control display unit, communications subsystem, and airborne computers were assumed to interface with the ground system, the Flight Plan Reference ground support equipment discussed in Section 4. The hybrid navigation systems assumed for the workload measurements utilized inputs from such subsystems as position fixing, air data, doppler, and INS systems in a variety of configurations. Each system incorporated a control/display device defined as an "air carrier control display unit", or a pictorial moving map display. The computer alternatives evaluated were the course line-computer, an area navigation and guidance computer, and an area navigation computer incorporating a vertical navigation channel. The primary communications and ATC surveillance link assumed for the evaluation was the VHF data link; a VHF voice capability provided a back-up. The airborne system performed as a complement to the ground Flight Plan Reference Concept.

TABLE XXXVII

AIRCARRIER AND GA3 ADVANCED NAVIGATION/TRAFFIC CONTROL SYSTEMS

AIR CARRIER AND GA3 SYSTEMS - LEVEL OF AUTOMATION	NAVIGATION						CONTROL DISPLAY		COMPUTERS			COMMUNI-CATIONS (o - voice as backup)		GROUND SYSTEM
	VOR NAV Comm Rec. DME Rec.	UHF NAV SAT Rec.	LF GBTD Rec.	Air Data	Doppler	INS	Control/Display Unit	MMD	Course Line Computer	Area NAV Computer	Area NAV Vertical Channel	VHF Voice Link	VHF Data Link	Flight Plan Reference
v1			x	x			x			x	x	o	x	x
v2			x	x			x	x		x		o	x	x
v3			x		x			x		x		o	x	x
v4			x	x		x	x			x		o	x	x
v5		x		x			x			x	x	o	x	x
v6		x			x			x		x	x	o	x	x
v7		x				x	x			x		o	x	x
v8	x				x				x			o	x	x
v9	x				x					x		o	x	x
v10			x		x			x		x		o	x	x

Table XXXVIII lists users of the candidate system. A broad range of candidate systems could meet the requirements of the typical IFR operation in domestic airspace. The candidate systems selected for evaluation are typical of those forecast to be available within the 1975-1985 time frame. Landing systems compatible with these primary systems are discussed in the sections which follow the review of candidates listed below.

6.3.2.1 System Levels of Automation

6.3.2.1.1 System Candidates

The candidate system level of automation are tabulated in Table XXXVII.

TABLE XXXVIII
CANDIDATE SYSTEM USERS

SYSTEM	Domestic System Route Structure Use	VTOL	VTOL/ Helicopter	STOL	GA3/ CTOL	SST
v1	Short Haul	x		x	x	
v2	Short Haul	x		x		
v3	Short Haul - Terminal Area Altitudes	x	x	x		
v4	Long Haul				x	x
v5	Short Haul	x		x		
v6	Short Haul - Terminal Area Altitudes	x	x	x		
v7	Long Haul				x	x
v8	Short/Long Haul	x	x	x	x	x
v9	Short Haul	x	x	x	x	
v10	Short Haul*	x	x	x		

*Air Taxi

The systems v1 . . . v10 are organized to represent varied levels in automation of the navigation system, communications link, and computer sophistication. The baseline systems are v8 and v10. Pilot workload is evaluated for each system type (v1, v2 . . .) to determine variations in pilot workload and the benefit derived by increasing the automation.

6.3.2.1.2 Primary Surveillance

The VHF data link generates the primary surveillance information used by the ATC system upon interrogation. The voice link is used as a backup system.

6.3.2.1.3 Primary Method of System Use

The candidate air carrier and GA3 systems are used by the pilot in accordance with the IFR Event Sequence Diagram contained in Appendix A. The navigation management event sequence diagram, also contained in Appendix A, is applied to the systems candidates. The results are contained in Appendix G.

Appendix G defines system operational sequencing, lists task times and percent utilization of pilot capacity in operating the equipment. The control display units assumed for operation of the systems are discussed. The functions, modes, and desirable operational characteristics of the "air carrier" control display unit and the pictorial moving map display are also defined in Appendix G.

6.3.2.1.4 VTOL Aircraft System v1

Figure 63 shows a signal flow diagram for the VTOL GBTD radio/air data area navigation system. Figure 64 shows the data link interface. The user mission is the domestic short haul air carrier route. Variants of the system meet the requirements for helicopter, STOL, CTOL and GA3 aircraft operations. The version illustrated is postulated for a VTOL 60-90 passenger vehicle.

System operation is defined in Appendix G. The air carrier control display unit is a typical panel control unit used to display operational modes: POS, WPT, HDG/DA, etc. The normal mode of operation is the cross track/track angle error (XTK/TKE) mode, with suitable outputs to the pilot.

The area navigation computer is the focal point of the system. Figure 63 shows the horizontal navigation channel. Sensor inputs are TD1, TD2 from the GBTD receiver; time (GMT), and heading from a magnetic compass. The air data system feeds TAS to the system. Principal data inputs to the system are: wind speed and wind direction; fix latitude, longitude; track/waypoint sequence; and ground based system chain setting. The standard pilot report data block is input to the VHF data link from the computer and is dumped when the surveillance interrogation pulse is received from the control unit,

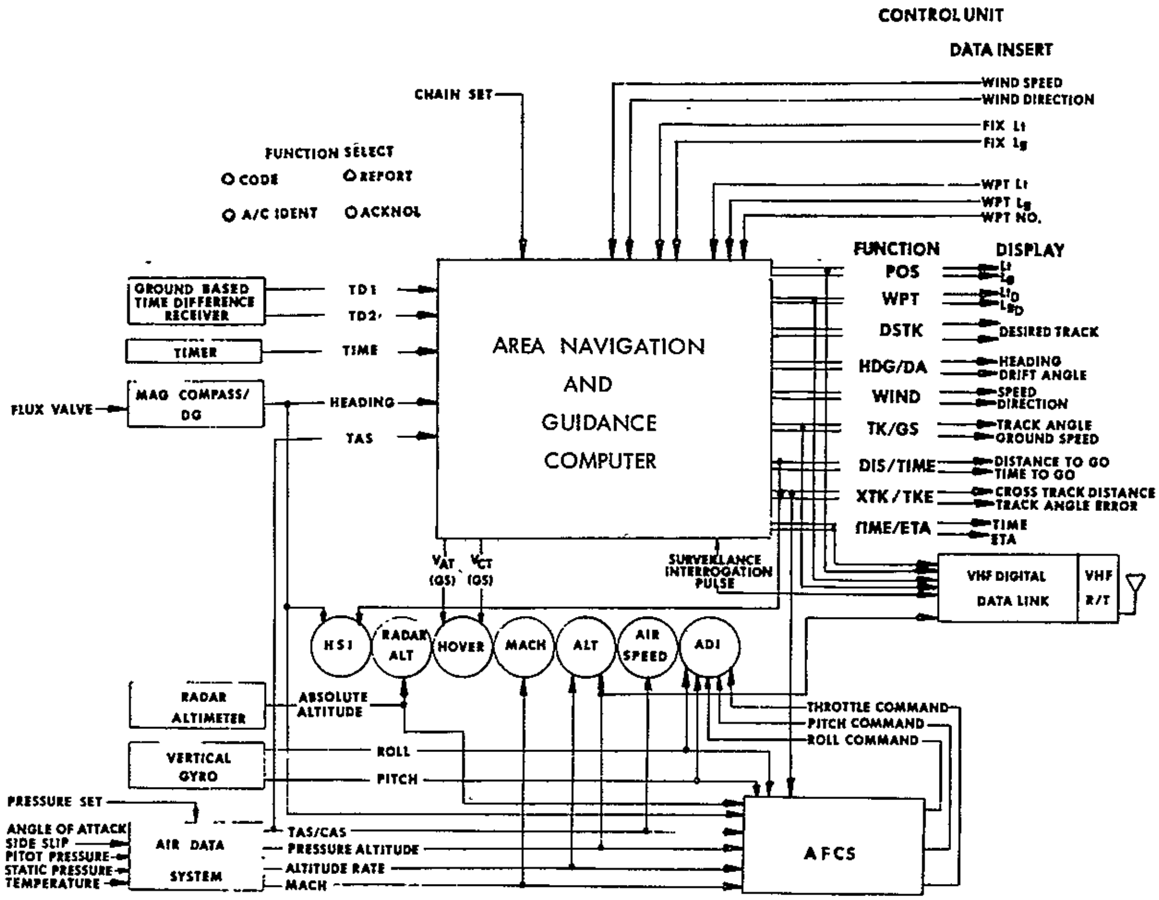

Figure 63. VTOL Aircraft GBTD Area Navigation System v1

or when a mandatory reporting point is overflown. The system also outputs along- and cross-track speed to the hover meter, and track angle error and cross track distance to the autopilot. The system is intended to interface with a conventional HSI by providing Distance to Go, Cross Track Distance and Steering Error or Track Angle Error (DTG, CTD, TKE).

The computer algorithms include:

(1) linearized solution of position fix

(2) coordinate conversion of M/S station location to lat/long

(3) coordinate conversion of present position to lat/long (see Appendix D) which illustrates linearized solutions about previous A/C position estimates

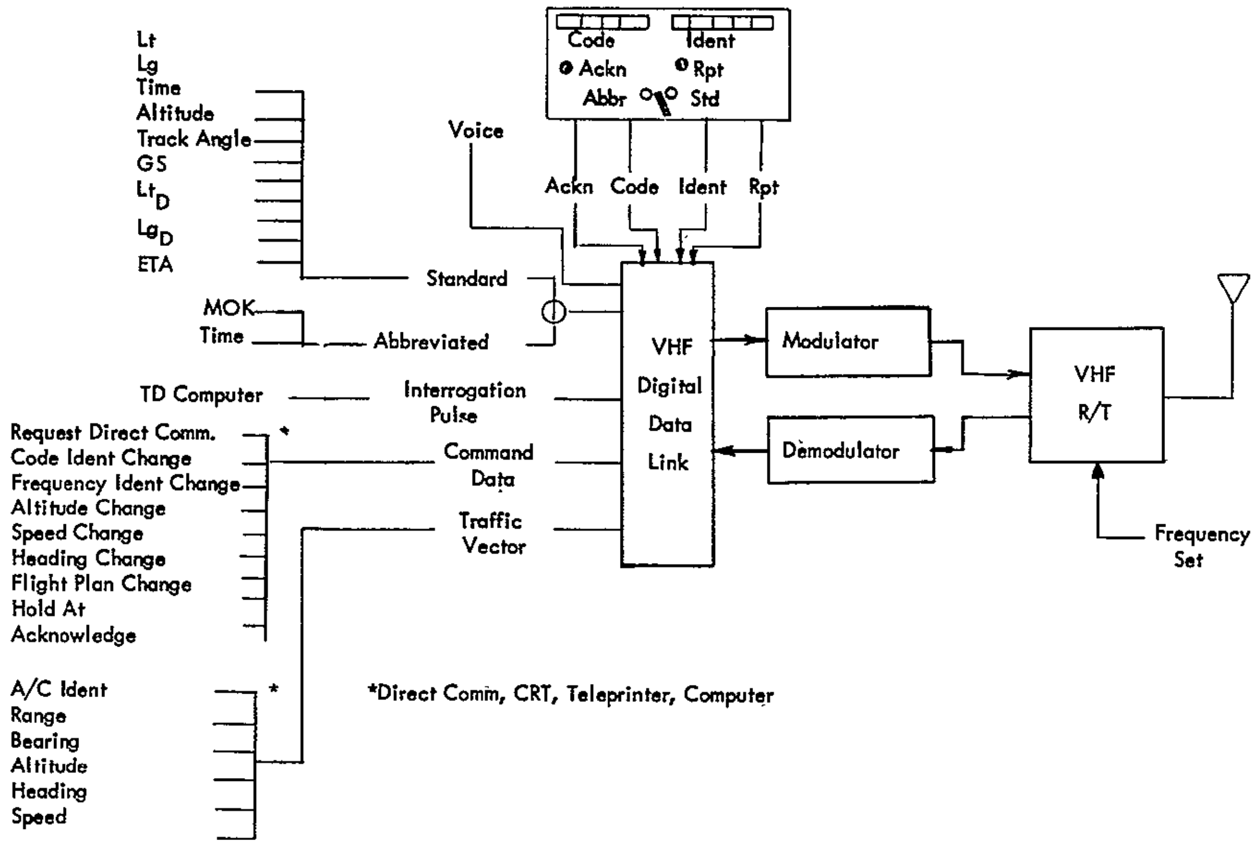

Figure 64. ATC VHF Data Link

(4) Short term air data DR solutions which add position movements to aircraft lat/long, thereby compensating for position update delay times in the airborne computer

(5) Coordinate conversion of coded waypoints whenever they are not in memory

(6) Great circle solution for desired course (called desired track angle (DSTK) by ARINC)

(7) Wind solution for wind along track, wind cross track

(8) Ground speed (GS) and actual track (TK)

(9) Distance to go (DTG) and time to go (TTG)

(10) Steering solution in terms of track angle error (TKE)

(11) Cross track distance (CTD)

(12) Output to AFCS, CTD and TKE (rate computation occurs in the AFCS computer)

(13) For those systems using a MMD, the aircraft coordinates Lt, Lg must be converted to pen x, y; cross track distance is converted to the MMD signals and TKE converted to the map display format

(14) Limit Logic computations and report release

(15) Automatic leg changeover

(16) Automatic determination of Start Turn Point to achieve track to track change;

(17) Automatic report downlink; without priority override, the algorithm tests the presence of an interrogation pulse; also command data dump when DTG = 0.

The variables are computed in a single iteration and stored until displayed or dumped. Nondestructive readout of coded waypoints is assumed; storage is used for chain identification and coordinate conversion of the master and slave stations to latitude, longitude; waypoint storage including mandatory report logic is assumed; altitude processing for glide slope computation; flight plan storage is provided.

Data link requires the input of aircraft identification code. A push button switch may be used to dump the data; acknowledgement and identification function are also provided for.

In addition to the air carrier control/display unit shown in Appendix G, a conventional hover meter, HSI, altimeter, radar altitude indicator, air speed indicator and an attitude director indicator complete the display complement.

The autopilot modes are described in Appendix G.

The ground system is the full flight plan reference concept.

Data Link

The system interface to the digital data link is expanded in Figure 64. The control unit shows that either of two reports can be selected. Provision is made for selecting either the standard report for use in uncongested airspace or an abbreviated report for use in congested areas. The code set specifies destination terminal and the responsible control unit. In addition, the pilot is provided with a mode which gives him the capability to override and to interrogate.

VTOL Automatic Flight Control System Integration

Figure 65 illustrates an integration of an area navigation system with the automatic flight control system of a VTOL aircraft. The navigation system computer inputs track angle error and cross track distance to the automatic flight control system.

The AFCS modes are designed to minimize pilot workload during climb, cruise and descent. Typical modes include attitude stabilization (for turbulence penetration), CAS or mach number hold, CAS or mach-altitude hold, ground track hold, heading hold, altitude hold and vertical speed hold. The desired mode is inserted into the flight director computer by the pilot's activation of the desired flight path hold configuration.

VTOL Flight Director Integration

Figure 66 shows the signal flow diagram of the VTOL aircraft area navigation and flight director computers. The flight director panel is defined in Appendix G for the horizontal flight modes. The area navigation computer outputs the signals: track angle error, distance to go, and cross track distance to the HSI.

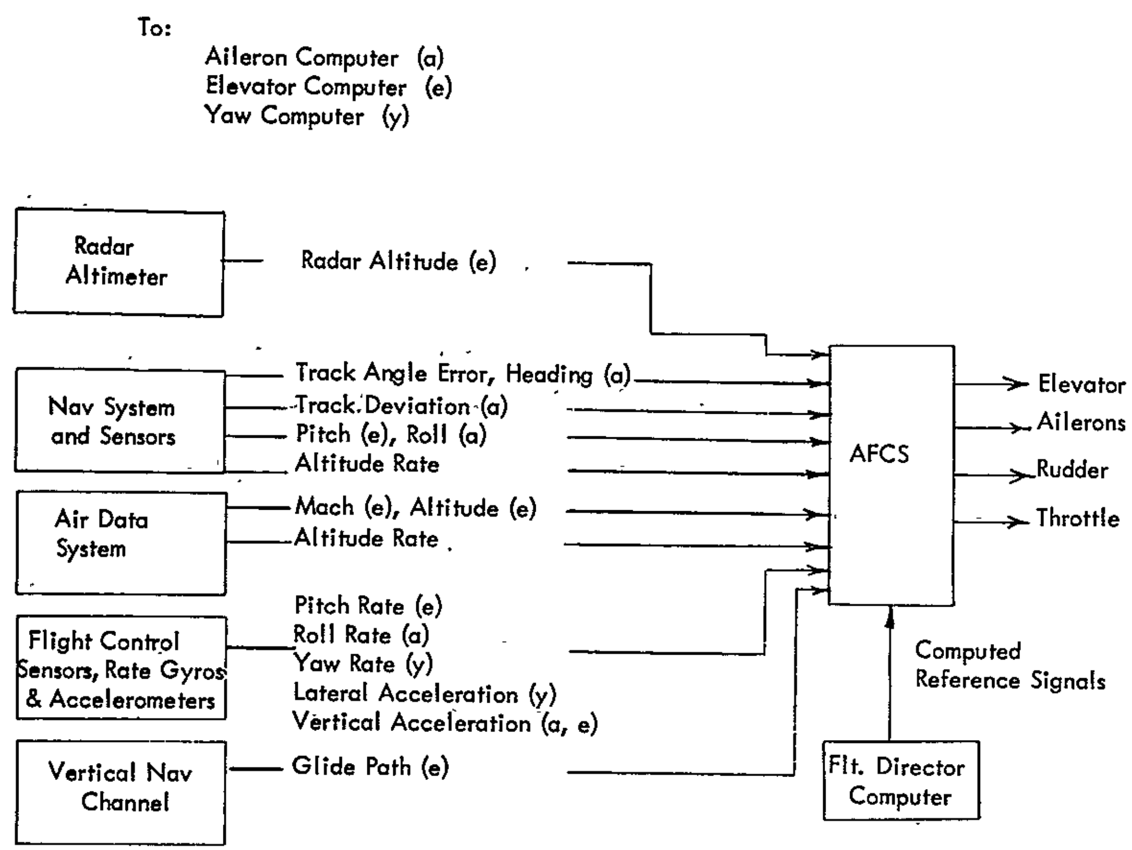

Figure 65. VTOL AFCS Integration

VTOL Precision Approach and Landing System

A candidate precision approach and landing system for VTOL aircraft utilizes a differential time difference NAV SAT or GBTD concept. The airborne system consists of a differential time difference (DTD) receiver, a time difference receiver, radar altimeter, marker beacon receiver, dead reckoning system and a vertical channel

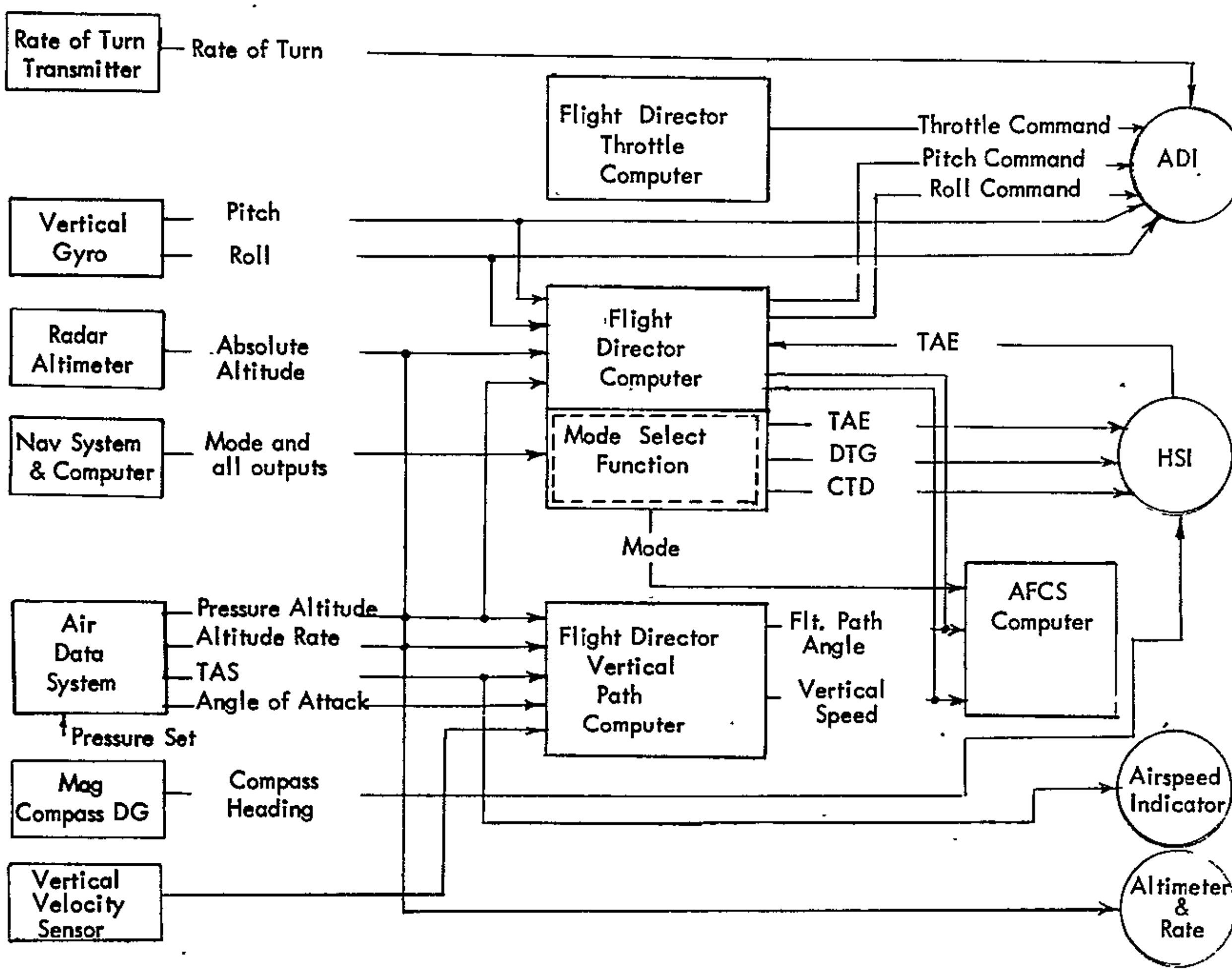

Figure 66. VTOL Flight Director Integration

computer system. The DTD system supplies long term, high accuracy horizontal navigational data. The signals are mixed with an output from the dead reckoning system to provide short term stability, and a calibrated radar altimeter updates inertial altitude at known points in the VTOL glide slope. In metropolitan areas, the known points could be keyed by marker beacons. Precision DME provides slant range distance to the landing pad. A forward-looking radar could be used to provide warning of obstacles in the flight path and to disclose the landing pad during instrument weather.

Figure 67 illustrates the landing geometry, while Figure 66 shows signal flow of the approach and landing system. Both horizontal and profile views of the landing geometry are indicated. In the concept suggested, four approach paths might be provided to the pad, each path employing a discrete frequency marker beacon. The marker beacons, located at, e.g. 7 and 3 nmi from the pad, could provide two functions: (1) the marker beacon would guarantee the integrity of the approach path if the beacons were frequency encoded; and (2) they could also provide the known ground points for altitude update. The INS would be updated by the radio system upon entry to the terminal area. The initial DTD signal would be used to calibrate the basic TD information on the landing zone. INS altitude would be updated at the outer and inner marker beacons. The land waypoints*: LWP1, LWP2 and LWP 3; and the landing pad LWP4; listed on conventional Approach Charts, could be stored in the airborne system. The altitude above sea level of each waypoint, the landing pad and the marker beacons would be known to the system. When the VTOL aircraft intersects IMB, the DME range would be gated into the automatic flight control system.

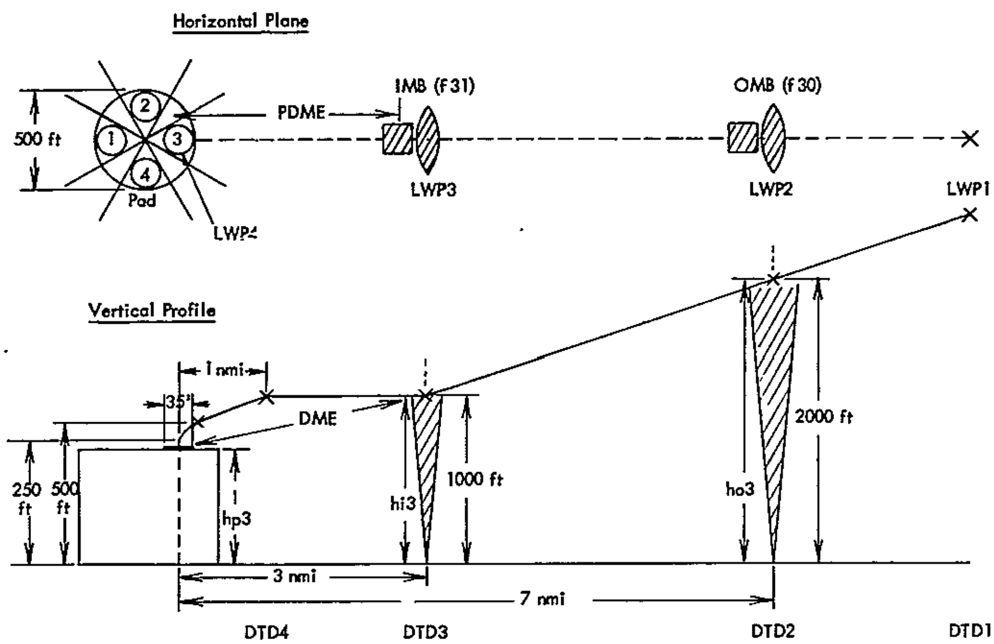

Figure 67. VTOL Landing System Geometry

*Land waypoint and final approach waypoint are terms which are synonymous for the purposes of this report

The navigation computer output to the AFCS is illustrated in Figure 68. The system is configured in the glide path mode. Speed reference V_{REF} is inserted; inputs become closure rate (DTG rate), track angle error, cross track distance and distance to go. In addition to these conventional signals, altitude deviation and command glide slope would also be provided. The PDME and radar updates are shown. The landing waypoints would be standard storage data.

6.3.2.1.5 VTOL Aircraft System v2

The VTOL aircraft area navigation system v2 is essentially identical to system v1; its principal difference is the provision of a moving map display. System v2 is a radio/air data area navigation system to be used by the short haul air carriers operating in the congested domestic airspace. The short stage-length system has appli-

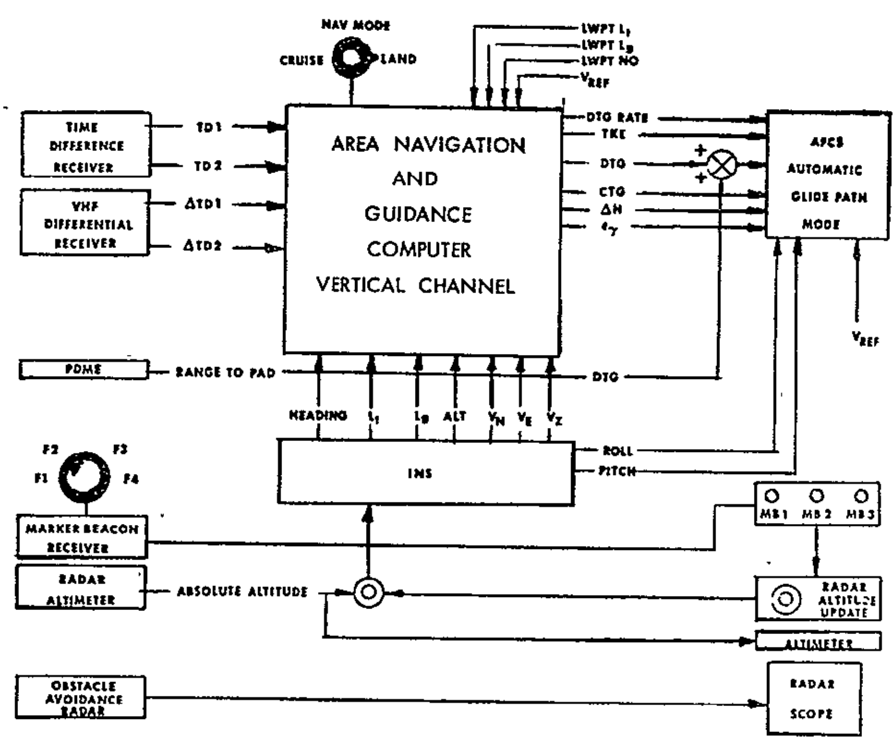

Figure 68. VTOL Aircraft GBTD/INS Landing System v1

cation to STOL aircraft and helicppter users, but the version shown in Figure 69 is typical of the large VTOL user (60 to 90 passenger).

The operational use of system v2 is discussed in Appendix G.

Two types of pictorial moving map display, varying in information content, were considered in this effort. The low-cost system provided a moving topographic chart on which was displayed aircraft track, aircraft position in latitude and longitude, and destination position in latitude/longitude. No command variables were displayed; the pilot was expected to compute cross track distance and track angle error from a mental picture of his relationship to desired track. The second system provided a pictorial display integrated with a horizontal situation instrument and the navigation management subsystem. Figure 69 illustrates the latter system in the context of a VTOL air carrier system. The

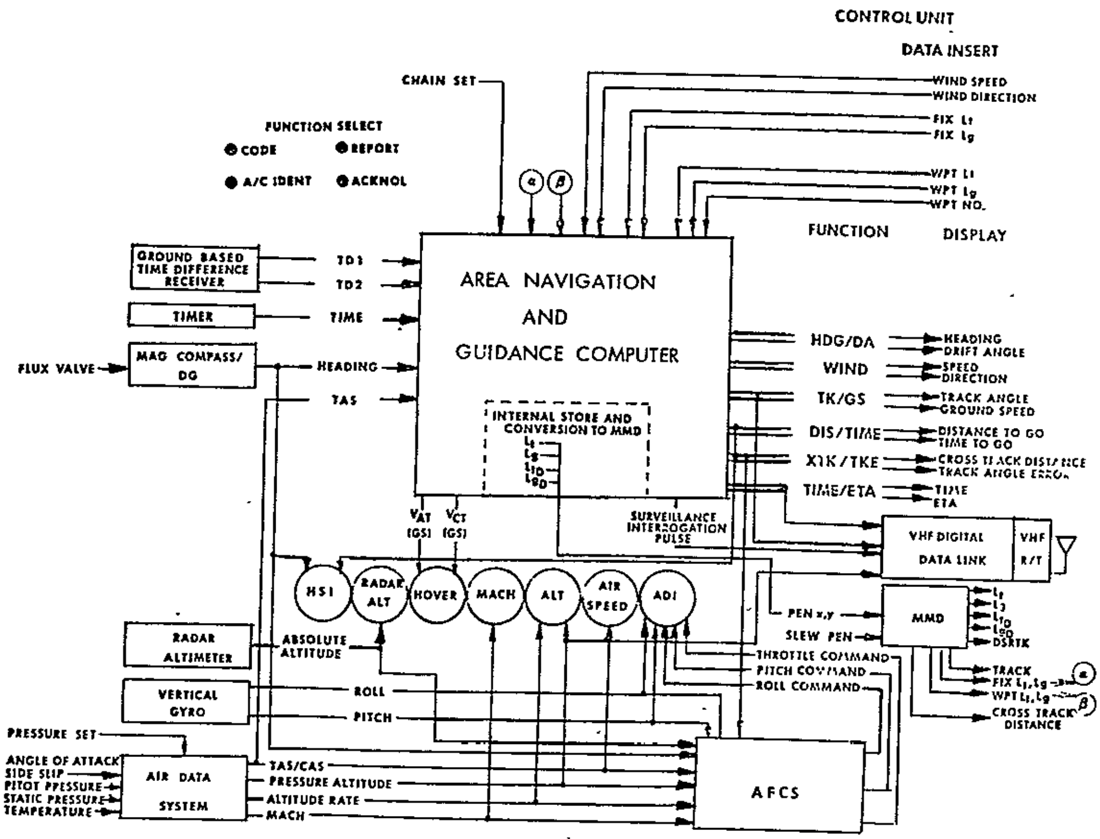

Figure 69. VTOL Aircraft GBTD Area Navigation, System v2

display provides desired track; aircraft position in latitude/longitude; waypoint displayed as a latitude/longitude readout; aircraft track, and aircraft cross track distance. Whenever the pictorial display is used to replace the horizontal situation indicator, an indication of track angle error is required.

The VTOL aircarrier system v2 is the equivalent in operation of systemvv1; however, the pilot's utilization of the systems differs. This difference is reviewed in Appendix G.

The implementation of computer computations, data link operation and flight control system integration of system v2 is identical to system vl. Differences include the computer algorithm, which provides for computation and generation of signals for the MMD; aircraft position and waypoint latitude/longitude are continuously computed and retained in memory; data insert of aircraft position to facilitate hyperbolic coordinate conversion is accomplished differently from that used in system vl; and system v2 uses the moving map display as a means to insert chart waypoints.

6.3.2.1.6 VTOL Aircraft System v3

This GBTD area navigation system also resembles system v1. The principal difference is the installation of a doppler radar which is integrated into the system to generate low speed velocity data for the VTOL aircraft during hover, final descent, landing and take off. The along track, cross track and vertical speed inputs are used for dead reckoning during terminal area and enroute cruise. Drift angle, which facilitates computation of wind components, is computed by the area navigation computer.

The system is applicable to the domestic short haul mission and applies equally, with modifications, to STOL and helicopter aircraft. The 60 to 90 passenger VTOL aircraft version is illustrated in Figure 70 . Figure 71 shows the landing system. The landing channel incorporates the doppler inputs.

The air carrier control display unit discussed in Appendix G, and the moving map display are used by the pilot in the navigation task.

The computer system performs the dead reckoning task utilizing inputs from the doppler.

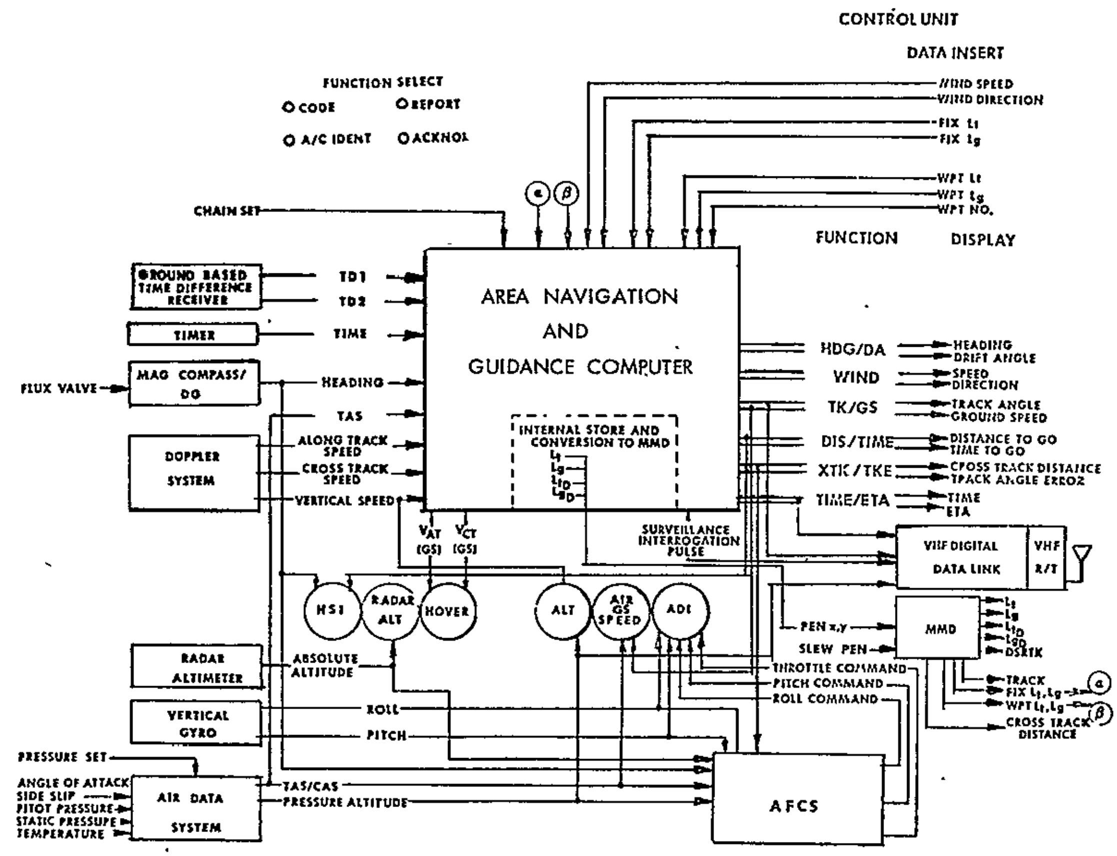

Figure 70. VTOL Aircraft GBTD Area Navigation System, v3

The input data is ground speed, cross track speed, and vertical speed. The area navigation computer derives drift angle and computes the dead reckoning solution.

Integration of the system is identical to that of system v1, with the same channels being used to integrate the area navigation system outputs with the AFCS, the flight director, and data link. This system is intended for use with the Flight Plan Reference ATC concept.

6.3.2.1.7 Air Carrier System v4

System v4 is designed to provide required navigation and ATC system information for CTOL jet and SST aircraft. It is designed to satisfy the long stage length or overwater application; however, it could also be used on the short stage length flown by

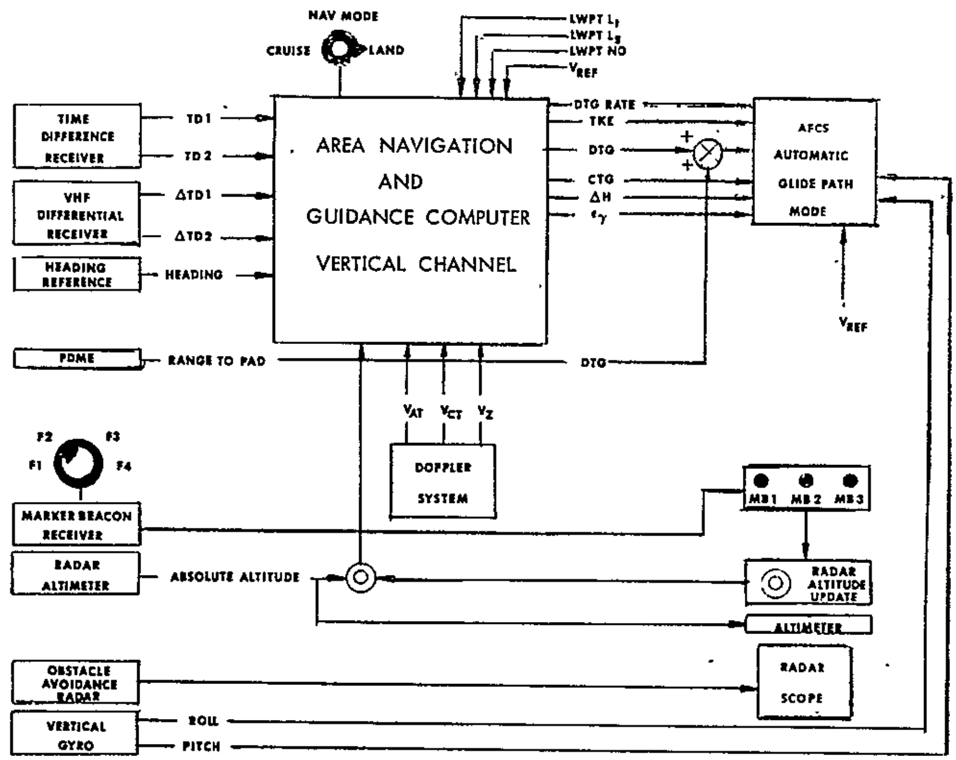

Figure 71. VTOL Aircraft GBTD Area Navigation Approach and Landing System, v3

VTOL. Figure 72 shows the system in the long stage length configuration. The VTOL version, which would include a hover meter output, has not been detailed; however, the landing version of this system is shown in Figure 73.

The INS is intended for use by CTOL and SST during the enroute portion of the flight. In the terminal area, the GBTD system as shown in Figure 72 would become the primary aid. For purposes of illustration, the INS is shown as a separate subsystem in the diagram. The INS computer would be integrated with the area navigation system and provision made for sensor signal mixing and data combination.

The system integration with the AFCS, flight director and data link is similar to that employed in system v1.

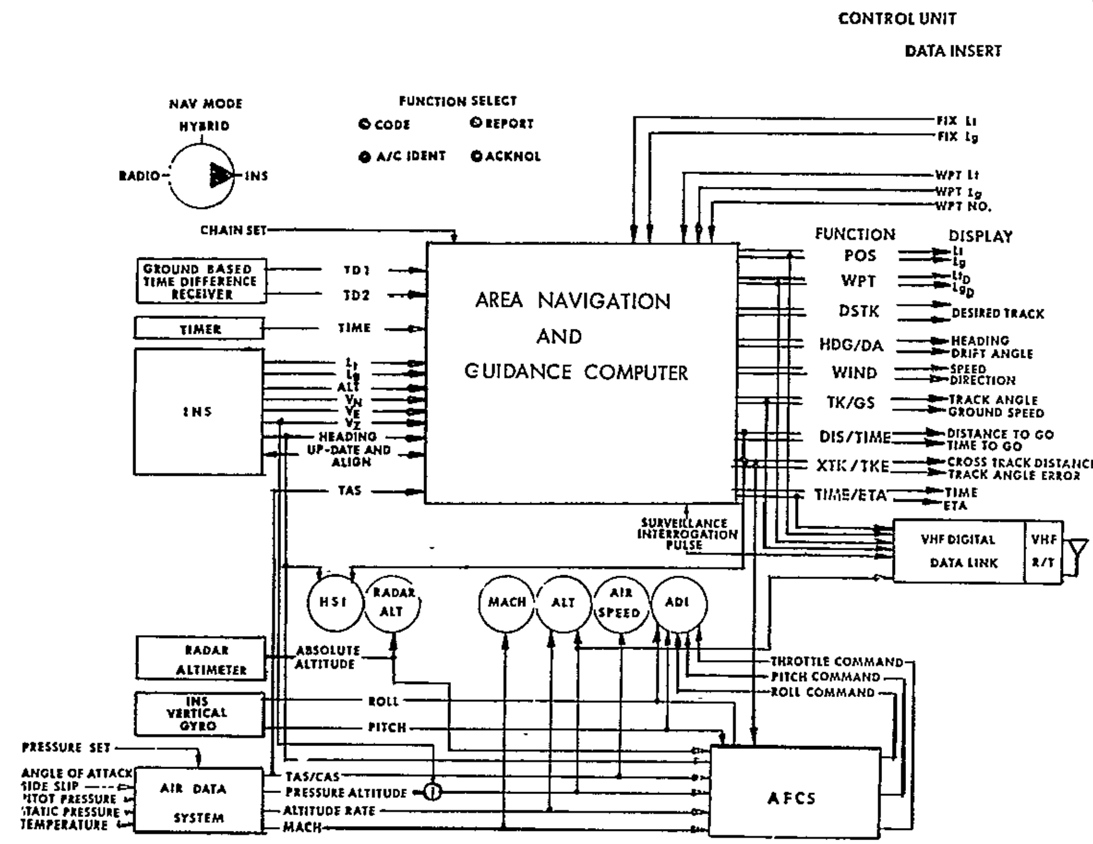

Figure 72. Long Haul GBTD Area Navigation System, v4

The landing system used by SST and CTOL was assumed to be either ILS or AILS.

6.3.2.1.8 VTOL Aircraft System v5

The v5 system was designed for use in the congested domestic short haul air-space, which includes the terminal area. The VTOL version of the system is shown in Figure 73 . The system could be utilized by STOL and CTOL as well. System level of automation for this NAV SAT/air data system is identical to system v1.

The area navigation and guidance computer solves for aircraft position from inputs of satellite emphemeris contents provided by the preprocessor and the L-band NAV

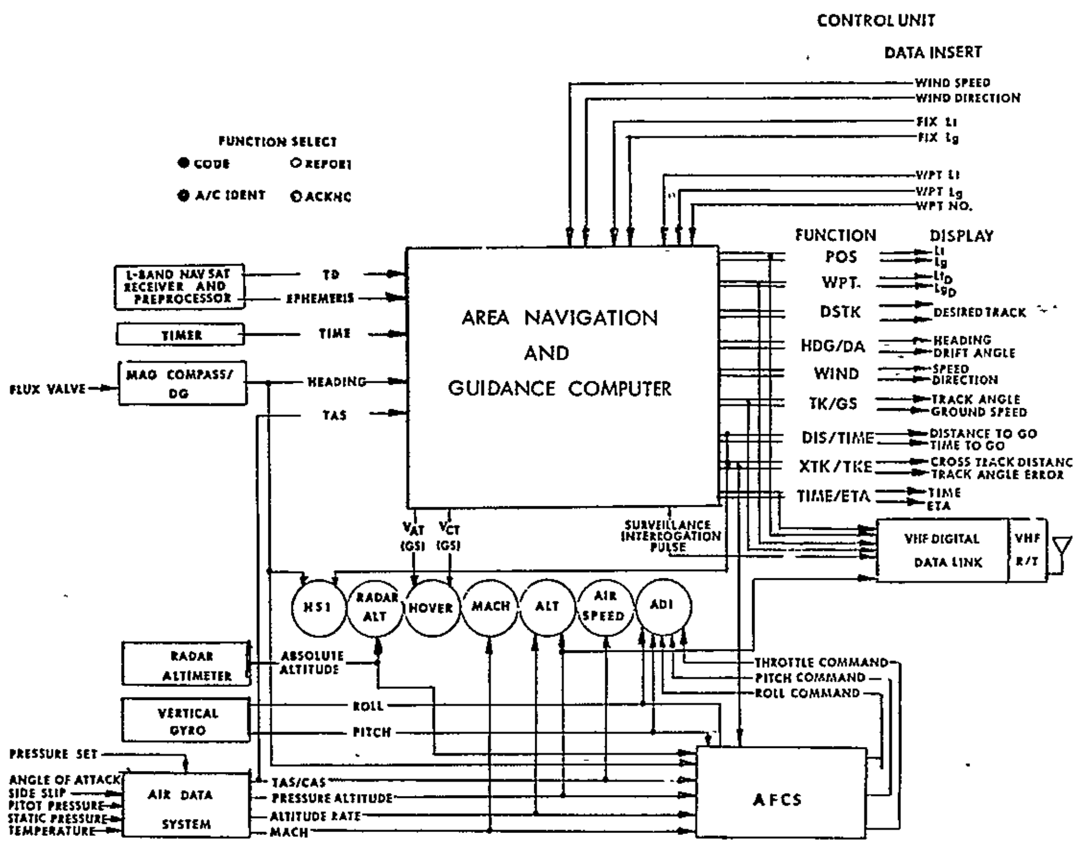

Figure 73. VTOL NAV SAT Area Navigation System, v5

SAT system. System data processing and utilization would be essentially the same as for system v1.

The precision approach and landing system, illustrated in Figure 74 is derived from a differential time difference NAV SAT configuration.

6.3.2.1.9 VTOL Aircraft System v6

The NAV SAT version of system v3, the system which employed a doppler radar, is shown in Figure 75 . System operation is described in Appendix G. System integration, operational characteristics and features are identical to those of systems v1 and v3. The NAV SAT area navigation system is principally a short haul terminal area

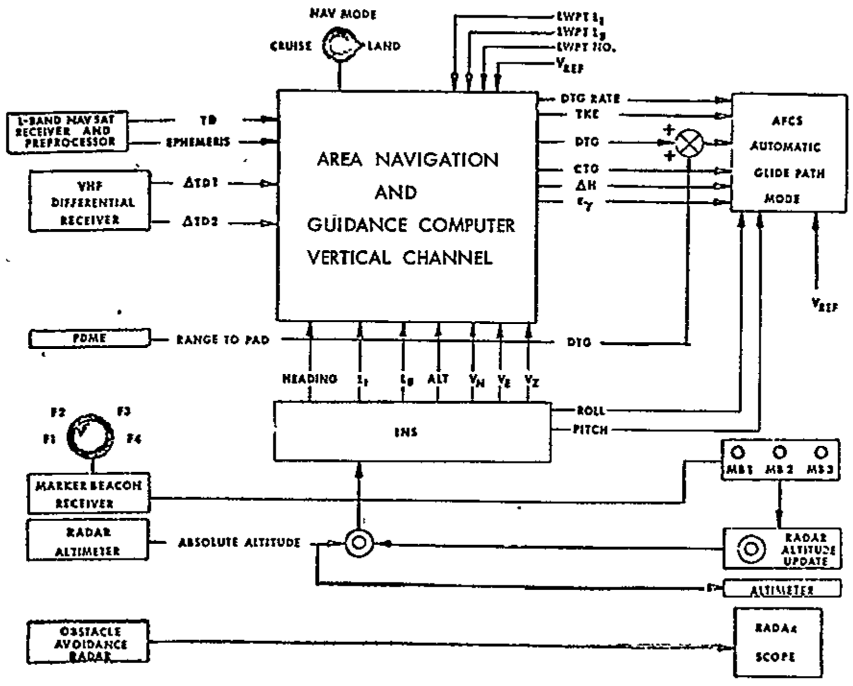

Figure 74. Differential Time Difference NAV SAT Landing System, v5

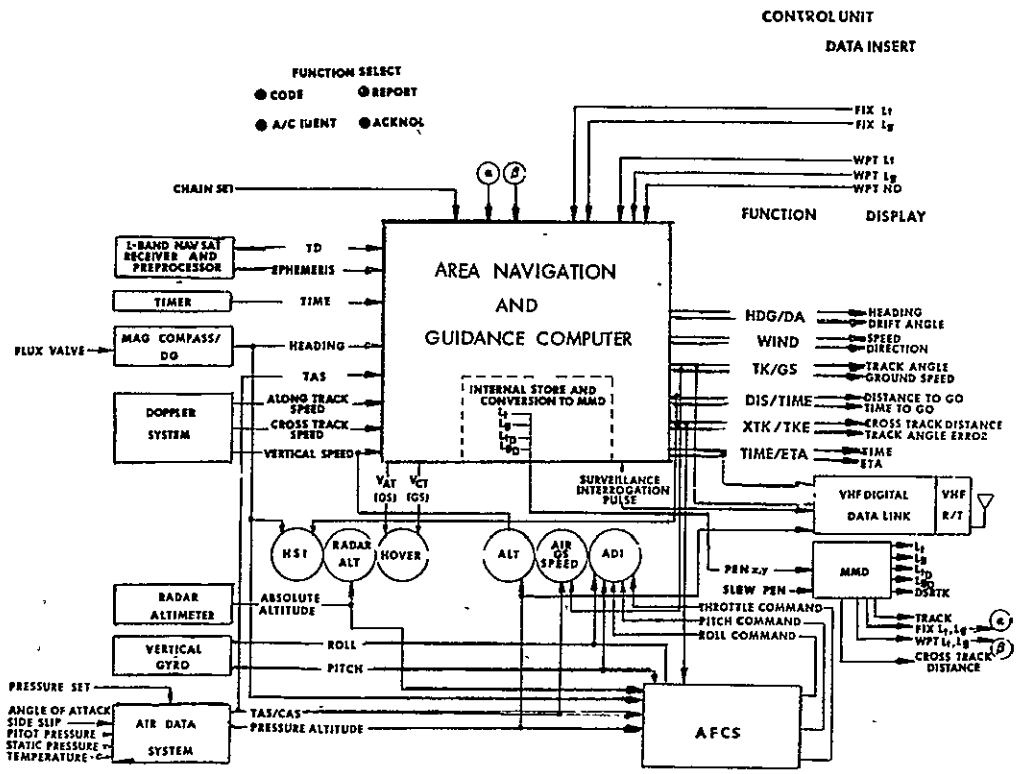

Figure 75. VTOL NAV SAT Doppler Area Navigation System, v6

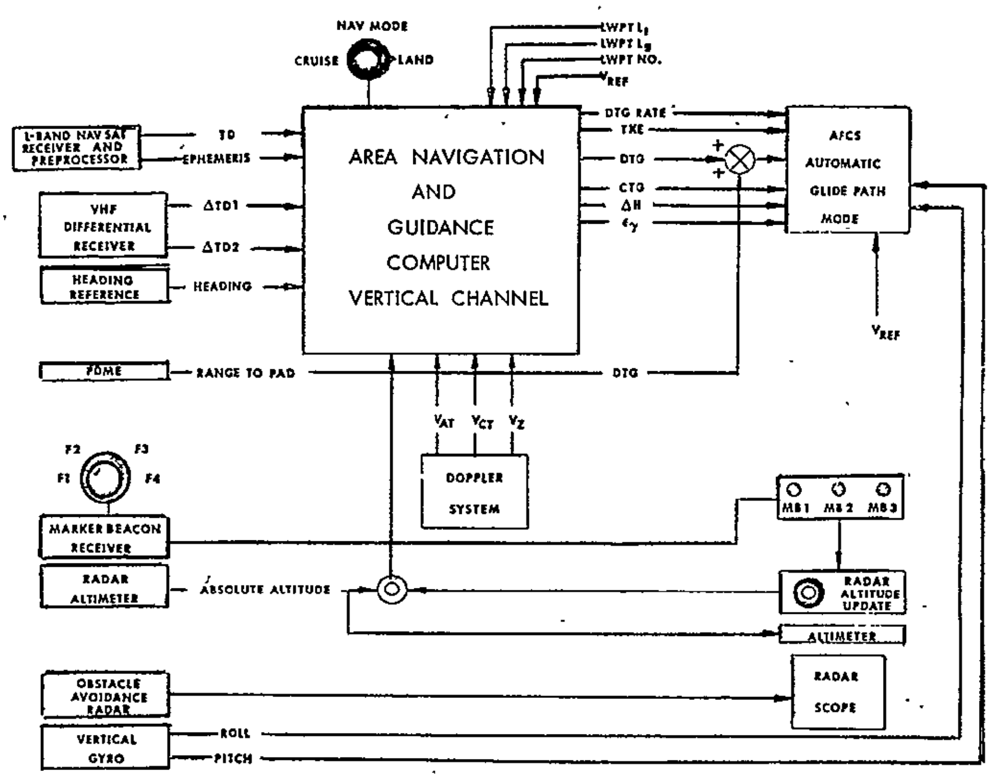

Figure 76. Differential Time Difference NAV SAT Approach System, v6

VTOL aircraft system, although applications for STOL and helicopter are feasible.

Figure 76 illustrates the differential time difference NAV SAT precision approach and landing system.

6.3.2.1.10 Air Carrier System v7

The principal difference between system v7 and v6 is that the doppler radar is replaced with an Inertial Navigation System. The radio-inertial configuration is suggested primarily for use by the CTOL and SST aircraft operating on long stage lengths.

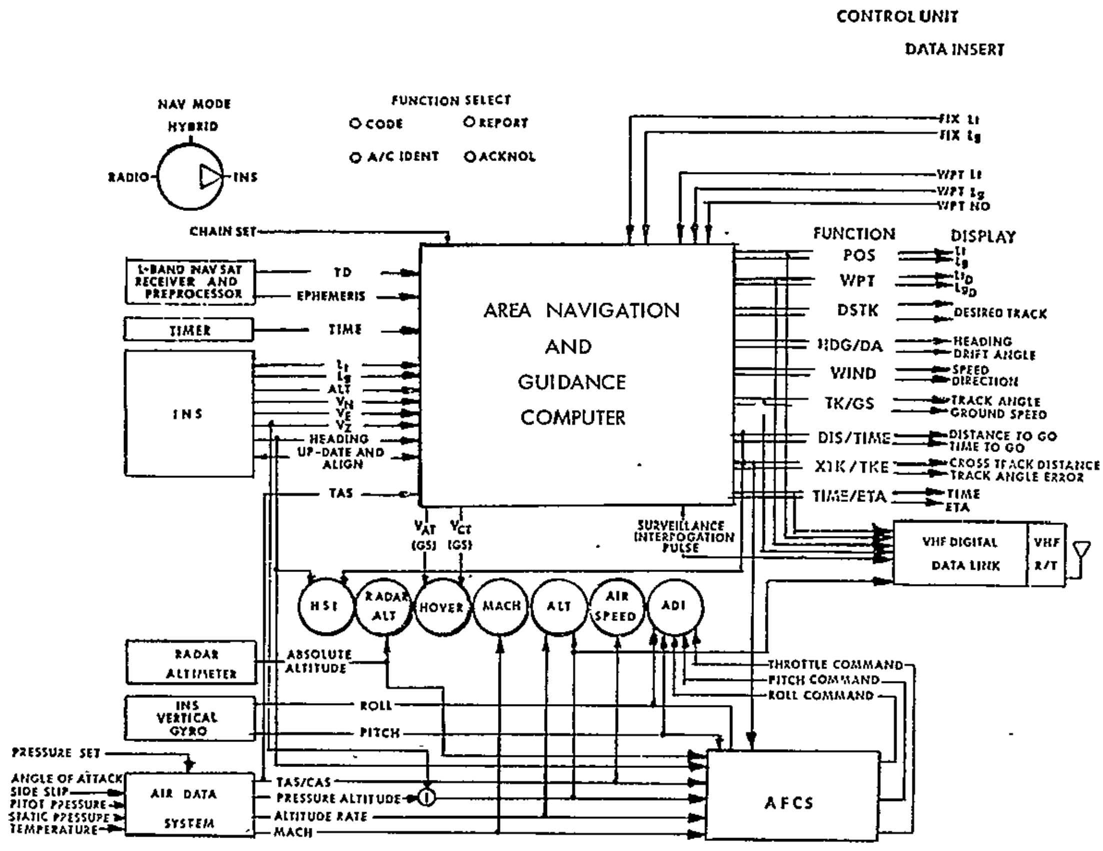

Figure 77. Long Haul NAV SAT Area Navigation System, v7

The significant characteristics of this kind of system were described earlier in this subsection; related pilot operations are described in Appendix G. The air carrier control display unit is used with the system. Figure 77 illustrates the signal flow diagram of the terminal area navigation system. The INS, although shown as an interface unit to the area navigation computer, is an integral component.

6.3.2.1.11 System v8

System v8, a minimally automated airborne system, utilizes PVOR/PDME and course line computer. The vehicles which could employ this system are VTOL, STOL, CTOL, GA3 and the air-taxi helicopter. The doppler radar system, used only in the

VTOL and helicopter applications, is limited to outputs of speed only. While no dead reckoning capability is offered by the system, the course line computer does output cross track distance and distance to go. System operation is explained in Appendix G.

6.3.2.1.12 System v9

By combining the area navigation and guidance computer functions of system v1 with the PVOR/PDME of system v8, an improved level of automation is achieved. The PVOR/PDME receivers supply range and bearing information to the area navigation computer. Coordinates of the waypoint (range and bearing from the ground facility) are inserted into the system. The coordinates of the facility are inserted as lat/long. The doppler radar completes the VTOL and helicopter requirement. The interface control unit is the air carrier control display unit. Computer system functions are analogous to those of system v1. The method of system use is defined in Appendix G.

Figure 78 illustrates the area navigation system in the air data mode. System operation and integration are also similar to system vl.

6.3.2.1.13 System v10

This minimally-automated GBTD system utilizes a moving map display. The air carrier control display unit is replaced with a moving map control display unit. The area navigation and guidance computer is of minimum size, complexity and functional capability. The user's operational steps are tabulated in Appendix G. The principal users of this system would be the 200 nmi, short haul carrier, e.g., the air-taxi operator, helicopter, VTOL and STOL aircraft. The VTOL versions would include a doppler system for speed inputs.

6.3.2.2 Air Carrier and GA3 Pilot Workload

Section 6.1 showed that workload experienced by the air carrier and GA3 pilot, as a result of normal tasks associated with control and monitor of his aircraft while

enroute, can be maintained at a low level with automation of the flight control system (AFCS). The advanced navigation/traffic control system has been designed to impose very little additional workload during performance of the system communication and management tasks while enroute. In the terminal area, however, workload will be significantly higher.

The specific navigation management workload for the ten system configurations discussed in this section is listed in Appendix D. The task details can be correlated with the navigation management event sequence diagram shown in Appendix A.

Report frequency, leg lengths, flight times and number of vectors received in the terminal area are subject to the following constraints. In congested airspace, mandatory reporting is assumed to occur every 50 nmi. In addition to this basic leg length, additional system reprogramming is assumed to occur on the short haul carrier leg lengths as listed in Table XXXIX.

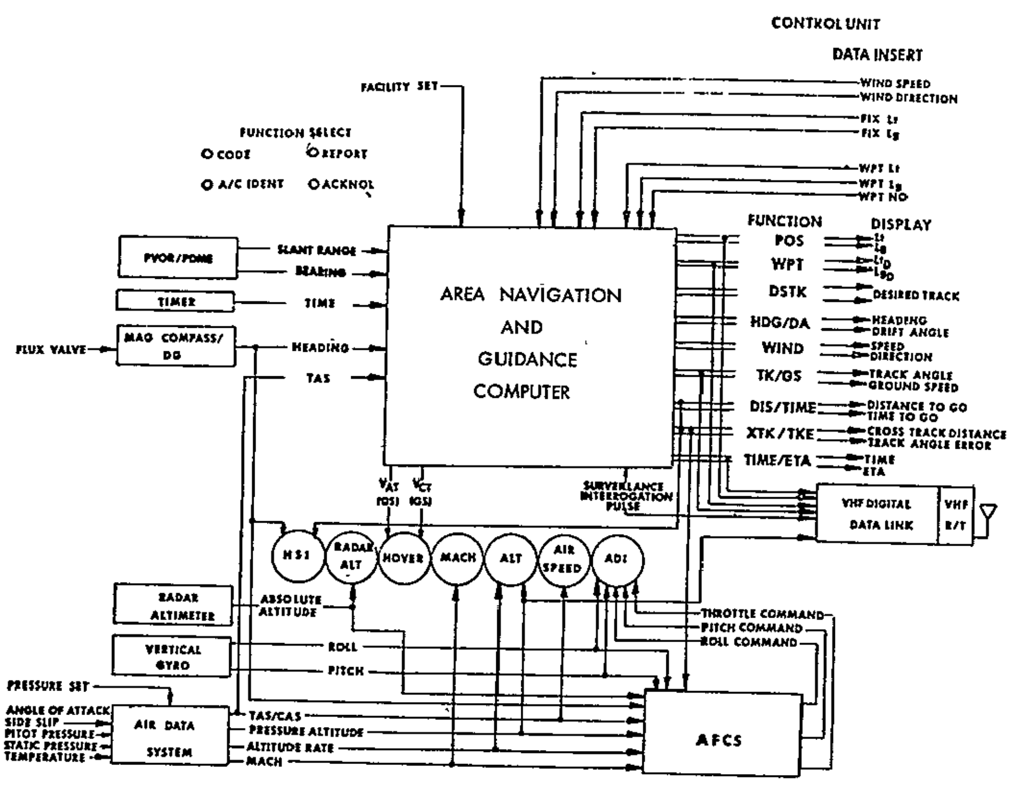

Figure 78. V-TOL Aircraft GBTD Area Navigation System, v10

TABLE XXXIX
SHORT HAUL LEG LENGTHS

System	Maximum Leg	Minimum Leg
NAV SAT	525 nmi	250 nmi
Ground Based TD - Short Chain	200 nmi	100 nmi
Ground Based TD - Long Chain	525 nmi	250 nmi
VORTAC (L) - below 18,000 ft	50 nmi	25 nmi
VORTAC (H) - above 18,000 ft	200 nmi	100 nmi

For purposes of estimating workload, experience has shown (Ref. 4) that command vectors issued by ATC during operation in the terminal area would average three per arrival and two per departure. Three vector waypoints were commanded prior to entering the terminal area.

Other constraints imposed on the air carrier pilot include:

(1) Assume that 8 waypoints will be used during the mission. For those systems (v1, v2, v3, v4, v5, v6, v7) which permit the waypoints to be stored prior to take off, no workload time was charged; for those systems (v8, v9, v10) which require inflight programming because of lack of system storage, workload execution time was charged.

(2) Assume that 3 of the 8 waypoints would be required for use in the terminal area as a result of a change in the flight plan by ATC. (charge of 3 wpts.) The charge to workload does not affect the systems in which the waypoints can be inserted while inflight.

(3) Eight (8) flight plan status checks were required of all systems

(4) An ATC report made on the downlink was required eight (8) times

(5) Assume that MET forecast will be updated once during the flight

(6) No diversions to other airfields would be required; however, the landing point must be initially programmed into the system

(7) Surveillance link set . . .

1	Departure
2	Enroute
1	Arrival

Total: 4 (+ 2 ATC changes) = 6

6.3.2.2.1 Total Inflight Navigation Management

The area navigation system and onboard automation should permit flexibility of operation and selection of flight path in both the terminal area and while enroute. In the latter case, flexibility must be maintained because of the need to avoid weather, effect flow control, or to select a new destination, thus requiring a change of clearance and therefore a change of stored flight plan data. Figure 79 summarizes this need for flexibility as applied to flight plan changes. The workload chart shows % pilot utilization and task execution time for the following tasks:

(a) system program inflight (mandatory 8 WP, 3 LWP)
(b) system reprogram inflight (3 WP)
(c) set surveillance link (single time)
(d) acquisition of steering data
(e) flight plan status check
(f) inflight land waypoint system program

Figure 79 shows that the total navigation management task load is uniformly distributed over the entire flight. As the level of automation of the system is increased, workload can be reduced to a level compatible with the requirements for efficient operation in the 1985 terminal area. Systems v1, v4, v5 and v7 experience a reduction to inflight workload of 82% as compared with the baseline area navigation/CLC system, system v8. Use of systems v2, v3 and v6 can provide a reduction in workload of as much as 88%. The use of an area navigation computer such as was postulated for system v9 requires 33% less work on the part of the pilot in comparison to system v8. System v10,

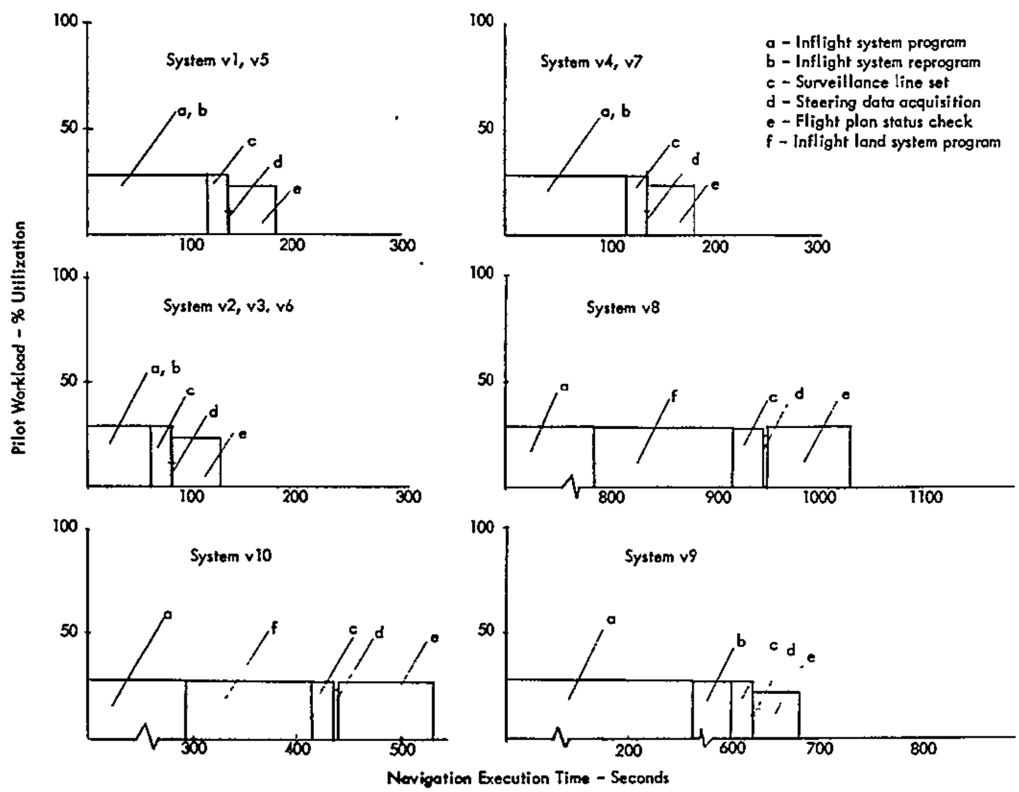

Figure 79. VTOL Pilot Navigation Management Workload

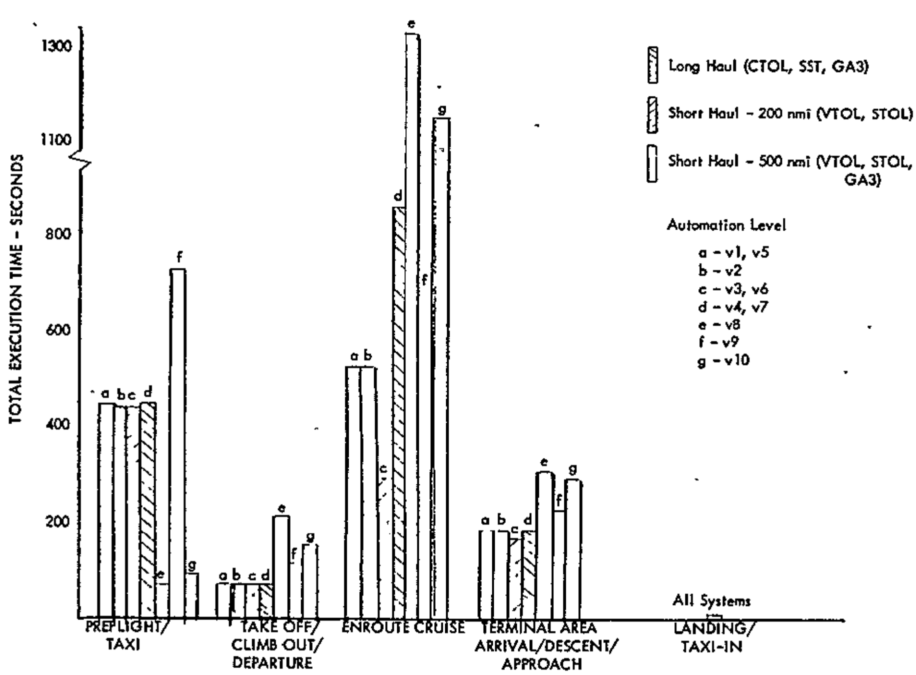

Figure 80. IFR Navigation Management Workload Summary and Automation Tradeoff

the minimally automated GBTD system, reduces inflight workload by 49%.

The computational capability of systems v1 and v5 results in a 66% reduction in inflight workload as compared with system v10. When the systems are equipped with the internal flight plan Limit Logic, the flight plan status check (e) as shown in Appendix G is reduced from 89 seconds to 3.2 seconds. This includes fuel remaining and altitude check. System v8, a VOR/DME CLC system which does not permit flight plan insertion, is not amenable to use of the Limit Logic function. Therefore, the time required for flight plan status check cannot be reduced below 89 seconds. This reduction in task execution time becomes significant whenever the flight plan checks must be repeated frequently, as on a short haul flight.

Utilization of an intermediate system containing a moving map display which does not permit preflight insertion of waypoints results in a significant increase in task execution time. Note the results tabulated below; the major difference between the two systems is the lack of storable waypoints in system v10.

v3	v10 (v3 less computer store)
(a, b) 60 sec	(a) 291 sec
	(b) -
(c) 20 sec	(c) 20 sec
(d) 1 sec	(d) 5 sec
(e) 45 sec	(e) 89 sec
(f) -	(f) 122 sec

This system might be more suitable to implementation in a helicopter system where lower cost is a significant factor in selection of hardware. The use of even a simplified moving map display (MMD) Control/Display Unit can reduce the workload associated with systems v1 and v5 by as much as 30%.

The ten systems are ranked in order of increasing inflight workload (or increased system penalty) as follows:

(1) Short Haul and Terminal Area

(lowest execution time)	(a)	v2, v3, v6	GBTD and NAV SAT with area navigation computer and MMD
	(b)	v1, v5	GBTD with area navigation computer
	(c)	v9	PVOR/PDME with area navigation computer
	(d)	v10	GBTD and NAV SAT with MMD
(highest execution time)	(e)	v8	PVOR/PDME with CLC

(2) Long Haul

(lowest execution time)	(a)	v4, v7	GBTD and NAV SAT with INS
(highest execution time)	(b)	v8	PVOR/PDME with CLC

6.3.2.2.2 Inflight Navigation Management Automation Benefits

Figure 80 summarizes navigation management workload for the entire flight profile. Although the preflight workload of the minimally automated systems, v8 (VOR/DME with CLC) and v10 (GBTD, NAV SAT with a moving map display), are minimum, the inflight workload in terms of total execution time is substantially higher for both systems than it is for the other eight. The total preflight workload for systems v1, v2, v3, v4, v5 and v6 (which include the area navigation system and unautomated flight plan reference system)is four times greater than systems v8 and v10. The preflight workload for a system which utilizes an area navigation and flight plan reference computer integrated with the VOR/DME system (v9) is seven times as great as for systems v8 and v10. However, the following inflight benefits are achieved:

Terminal Area: The benefits in terminal area workload relative to (and using) system v8 are:

System	% of baseline system workload
v8 (VOR/DME CLC) -	100 % (baseline)

v9 (VOR/DME with full area navigation/ flight plan reference computer) - 65%

v10 (minimum automation, GBTD with MMD) - 77%

v1, v4, v5, v7 (maximum automation GBTD, NAV SAT with area navigation/flight plan reference computer) 50%

v2, v3, v6 (maximum automation GBTD, NAV SAT with area navigation/flight plan reference computer and MMD) 50%

Enroute: Values for the 500 nmi short haul mission workload, (in terms of system v8), are:

v8 (VOR/DME CLC) - 100%

v9 (VOR/DME with full area navigation/ flight plan reference computer) - 52%

v10 (minimum automation GBTD with MMD) - 86%

v1, v5 (maximum automation GBTD, NAV SAT with area navigation/ flight plan reference computer, and MMD) 38%

6.3.2.2.3 Communication Automation Benefits

Automation of the communications link results in a substantial reduction in total task-execution time. Figure 81 illustrates the relative benefits derived from different levels of automation of data link. The system levels of automation for systems v1... v10 were exercized through the IFR event sequence diagram, Appendix A. The results,

tabulated in Figure 81, report reduction in total execution time for the A-G, G-A message execution times.

The four levels of automation are:

(1) Automation of the Standard Report

(2) Automation of the A-G Acknowledgement

(3) Automation of the Command Control G-A

(4) Automation of the Advisory messages

Advisory automation could be implemented by using an onboard teleprinter, or CRT readout. The command function is implemented by a direct input to the airborne computer from the ground computer and is subsequently displayed on a CRT or teleprinter. Thereafter the pilot accepts or rejects the ATC command by utilizing the automated acknowledgement capability.

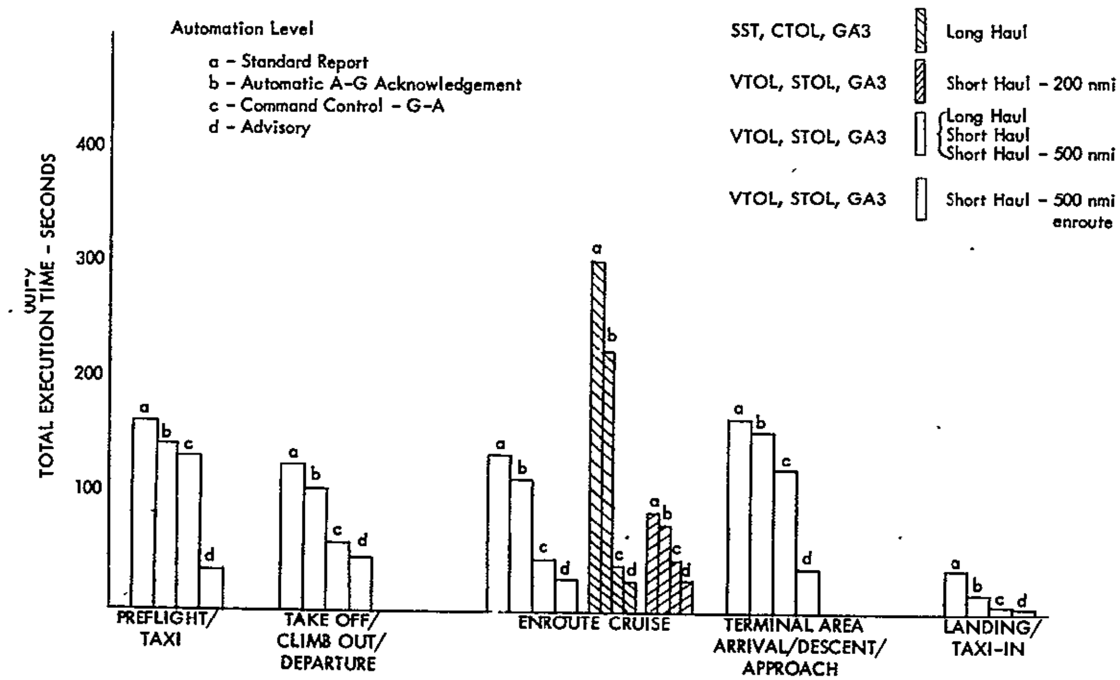

Figure 81. IFR Communications Workload Summary and Automation Tradeoff

Using the automated standard report as the baseline, the following automation benefits are obtained:

Enroute

Long Haul Mission:

Standard Report -	100%
Automatic A-G Acknowledgement -	74%
Command Control G-A -	13%
Advisory	11%

500 nmi Short Haul Mission:

Standard Report -	100%
Automatic A-G Acknowledgement -	85%
Command Control G-A -	31%
Advisory -	21%

200 nmi Short Haul Mission:

Standard Report -	100%
Automatic A-G Acknowledgement -	88%
Command Control G-A -	53%
Advisory -	33%

Terminal Area

Standard Report -	100%
Automatic A-G Acknowledgement -	88%
Command Control G-A -	59%
Advisory -	28%

The automation of the communications link - to include surveillance reports and a selective calling capability - significantly reduces pilot workload.

6.3.2.2.4 Navigation Workload Automation Benefits

The navigation management workload can be further reduced by implementing the Flight Plan Reference System, as the information presented in Figure 82 indicates.

In this evaluation it was assumed that use of coded waypoints would be utilized inflight to facilitate any required reprogramming. During this evaluation it was assumed that the only required inflight reprogramming of stored waypoints would occur in the terminal area. The results tabulated in Figure 82 show that the most significant

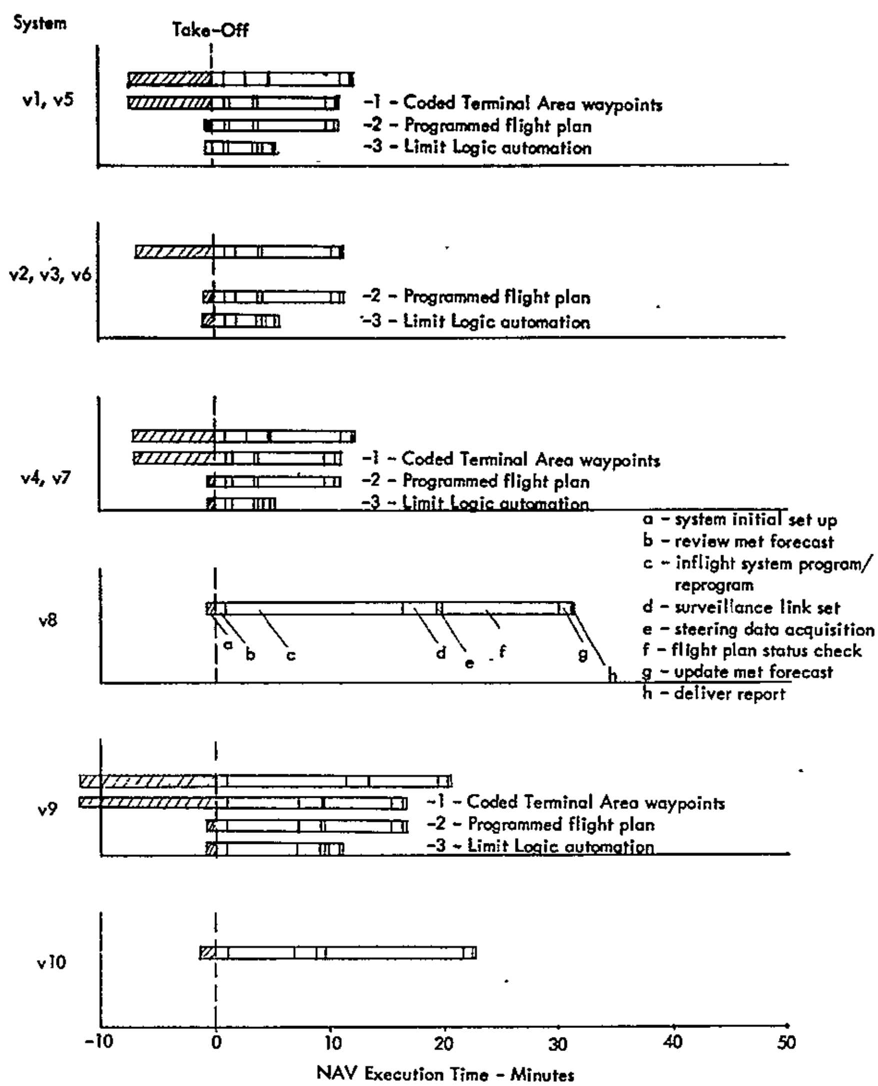

Figure 82. VTOL Pilot Navigation Management Workload - Automation Tradeoff

decrease in workload results from use of the Limit Logic technique - that is the automatic process used onboard the aircraft to continually compare actual flight progress with the approved (and stored) flight plan. The results pertain only to systems in which a general purpose computer is provided, e.g. v1 through v7 and v9. The two low cost baseline systems, v8 and v10, do not contain a general purpose computer capability and thus cannot utilize the automated Limit Logic.

Thus the availability of coded waypoints reflects in a greater reduction in workload for this function in system v9 than is the case for the other system.

Flight Plan Insert

Full implementation of the Limit Logic concept requires that the Flight Plan waypoints and connecting flight paths be stored in the system and automatically made available to the Limit Logic subroutine as the aircraft proceeds along track. It should be noted that the system must retain the capability to introduce or to receive an amended clearance. Thus, automation of the flight plan insert process can reduce workload not only on the ground but also in the air.

In summary, workload can be reduced by implementation of the three items:

(1) Limit Logic
(2) Automated flight plan insert
(3) Use of coded waypoints

The benefits derived from automation of inflight navigation management functions are summarized in the following paragraphs. Benefits are quantified with respect to system v8, a VOR/DME plus CLC system which does not contain a capability for automation of the three functions.

v8 (VOR/DME with CLC):

Unautomated Flight Plan Reference	100%
Coded Terminal Area Waypoints	NA
Programmed Flight Plan	NA
Limit Logic	NA

v9 (VOR/DME with full area navigation/
flight plan reference computer)

Unautomated Flight Plan Reference -	100%
Coded Terminal Area Waypoints -	81%
Programmed Flight Plan -	81%
Limit Logic -	54%

v10 (minimum automation, GBTD with MMD)

Unautomated Flight Plan Reference -	100%
Coded Terminal Area Waypoints -	NA
Programmed Flight Plan -	NA
Limit Logic -	NA

v1, v5, v4, v7 (maximum automation GBTD NAV SAT
with area navigation/flight plan reference computer)

Unautomated Flight Plan Reference -	100%
Coded Terminal Area Waypoints -	91%
Programmed Flight Plan -	91%
Limit Logic -	54%

v2, v3, v6 (maximum automation GBTD, NAV SAT
with area navigation flight plan reference computer
and MMD)

Unautomated Flight Plan Reference -	100%
Coded Terminal Area Waypoints -	NA
Programmed Flight Plan -	100%
Limit Logic -	53%

SECTION 7

SYSTEM BENEFIT

7.0 SUMMARY

System Capacity Benefit and System Cost Benefit are two criteria which provide a measure of the relative effectiveness of the area navigation techniques - - navigational satellite (NAVSAT), ground based time difference (LF-CW, VLF-CW, pulsed) and precision rho-theta. These criteria express system benefit in terms of navigation system accuracy, pilot communications workload, pilot navigation management workload, and ground system costs. The criteria rank the area navigation technique in order of acceptability for integration with the Flight Plan Reference ATC system.

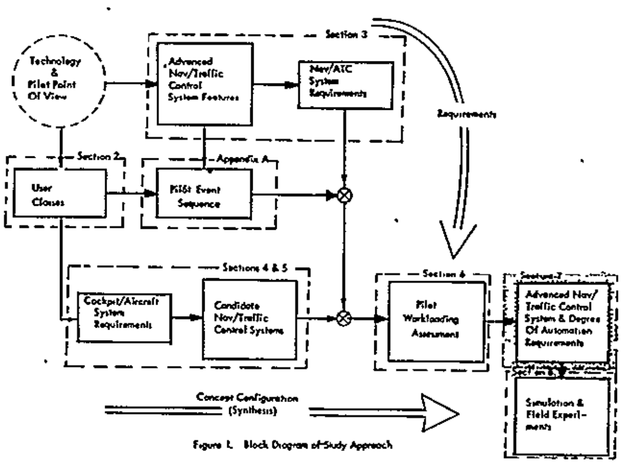

Figure 1. Block Diagram of Study Approach

The System Capacity Benefit shows that the NAV SAT candidate system yields the greatest benefits of any of the systems considered for the 1975-1985 advanced area navigation/traffic control system. The benefits from NAV SAT far outweigh the benefits to be derived from LF GBTD-pulsed, LF GBTD-CW, and the precision rho-theta systems. The rho-theta and VLF GBTD-CW systems rank as least effective as well as failing to meet the defined performance requirements.

The System Cost Benefit does not change the ranking. NAVSAT offers the greatest cost benefit; the long range LF GBTD-pulsed system is rated a close alternative. Third in ranking is the LF GBTD-CW system, while the precision rho-theta is rated the least cost effective.

In summary then, the order of ranking of the navigational aids which show the most promise is - - NAVSAT, GBTD-pulsed, GBTD-CW, and precision rho-theta.

SECTION 7

SYSTEM BENEFIT

Evaluation criteria used in making the assesment of system benefits from implementation of the NAVTRACS advanced area navigation/traffic control system are summarized in this Section.

Sections 4, 5, and 6 of this report provided the data which was used to assess system benefit. An effectiveness criterion for candidate navigation/traffic control systems was determined in terms of navigation system accuracy, pilot communications workload, pilot navigation management workload and ground system costs. The results of the system accuracy analysis, the pilot workload/automation trade off analysis, and ground system costs tabulation (Appendix E) are combined in this Section and presented in terms of: (1) System Capacity Benefit, and (2) System Cost Benefit. These two criteria provide a measure of the relative worth of the candidate area navigation systems evaluated in this study.

7.1 EVALUATION CRITERIA

Three factors used in this study to determine the relative worth of the candidate systems were a penalty criterion, a system capacity index, and system capacity benefit.

7.1.1 Penalty Criterion

The penalty criterion used in evaluating the candidate system seeks to relate system capacity, performance of the candidate systems and pilot workload. The following relationship is used:

$$P_S = A \cdot (B + C)$$

where: A = System $3\,\sigma$ accuracy

B = General aviation pilot communication and navigation management workload

C = Aircarrier communication and navigation management workload

Decreasing C implies that the pilot of the commercial aircraft is able to comply with short-notice changes in traffic control and that he is still able to perform other required aircraft management tasks. Decreasing B implies that the general aviation pilot is able to cope with the advanced traffic control system - in particular, that the general aviation pilot is not overloaded. Decreasing (improving) A implies the availability of more accurate surveillance data and the potential for closer spacing of tracks. Item A is bound by the constraints of the 1975-1985 navigation requirements as specified in Section 3.

The values of the system penalty criteria, A, B, and C are listed in Table XL.

TABLE XL
AREA NAVIGATION SYSTEM PENALTY CRITERIA

CANDIDATE SYSTEMS*	A** System Accuracy nmi	B*** General Aviation Pilot Comm. and Nav. Management Workload Total Mission Execution Time, seconds	C**** Air Carrier Pilot Comm. and Nav. Management Workload Total Mission Execution Time, seconds
Rho-theta (g13, v8)	1.3	4520	1510
Precision rho-theta (g14, v9)	0.5	3390	895
GBTD-VLF/CW (g12, v2)	6.6	3110	705
GBTD-LF/CW (g12, v2)	0.5	3110	705
GBTD-LF/Pulsed (g12, v2)	0.5	3110	705
NAV SAT (g9, v5)	0.1	3340	705

*Section 6.3
**Section 5 (Figure 31)
***Section 6.3.1 (Figure 62)
****Section 6.3.2 (Figure 81)

These values were derived from the data which are summarized in Sections 5 and 6. The system accuracy criteria (A) are defined in Section 5. The guidelines which were used to select the general aviation and aircarrier workload criteria (B and C) are:

(a) use maximum automation in the airborne system for a given baseline (NAV SAT, GBTD, etc.)

(b) use inflight workload in terms of total execution time

(c) use inflight workload for the total mission

7.1.2 Capacity Index

A relative capacity index is given by:

$$C_R = \frac{P_s \text{ (baseline system)}}{P_s \text{ (candidate system)}}$$

If C_R is greater than 1, the candidate system is more effective. For this evaluation the P_s for the Rho-theta system configuration was taken as the baseline value.

7.1.3 System Capacity Benefit

The relative weighting of the candidate systems is listed below in descending order of merit.

System Type	Example	C_R
NAV SAT	NAV SAT	19.3
LF GBTD-Pulsed	Loran C	4.1
LF GBTD-CW	Decca	4.1
Rho-theta	PVOR/PDME	3.7
*Rho-theta	VOR/DME	1.0
*VLF GBTD-CW	Omega	0.35

These data show that the NAVSAT candidate system yields the greatest benefits of any of the systems considered for the 1975-1985 advanced area navigation/traffic control system. Note that any reduction in the workload terms would be reflected across all the systems; thus the relative standings would not change. However, a modification to the stipulated value of accuracy for any one of the systems could significantly change its relative standing.

*Indicates that system does not comply with 1975-1985 traffic control navigation or communication operational requirement.

7.2 SYSTEM COST BENEFIT

If the capacity index, C_R, is further refined with a measure of system ground station and maintenance costs, the following performance index is derived:

$$C_s = \frac{C_R}{C_{\$R}}$$

where:

$$C_{\$R} = \frac{\text{Cost (candidate system)}}{\text{Cost (baseline system)}}$$

and where:

Cost = installation and maintenance cost for domestic U.S. airspace coverage (see Appendix E)

As in the previously discussed capacity index, the baseline system used in this cost index is the currently standard Rho-theta system.

Table XLI lists the supporting data which was used in the calculation of the cost ratio $C_{\$R}$. To permit the above computation of C_s, C_R is obtained from Section 7.1.

It should be noted that the values contained in Table XLI are approximations used to identify major relative differences in implementation costs. For this reason, the total cost figures must be considered in light of the following arbitrary assumptions used to develop $C_{\$R}$.

1) The single station total cost was predicated upon the summation of the initial implementation cost and one year's maintenance cost. No assumptions were made as to the total useful life of the system.

2) The total cost of each ground station complex was predicated upon the product of the single station total cost and the estimated <u>total</u> number of stations required. No attempt was made to separate out the costs incurred to date for existing installations. Therefore, the total cost figures quoted represent the <u>total</u> investment required to implement

the assumed number of stations. For the purposes of this analysis, this approximation is adequate and does not change the relative rankings.

TABLE XLI
ESTIMATES OF GROUND STATION AND MAINTENANCE COSTS

System Type	Single Station Total Cost $\$ \times 10^6$	Ground Station Yearly Maintenance Cost $\$ \times 10^6$	Ground Station Cost $\$ \times 10^6$	Estimated* Number of Installations	Total Cost $\$ \times 10^6$	$C_{\$R}$
VOR/DME	0.23	0.03	0.2	1500	350	1
VLF GBTD-CW	9.3	0.3**	9.0	4	37.2	0.106
PVOR/PDME	0.23	0.03	0.2	1500	350	1
LF GBTD-CW	1.55	0.05	1.5	60	93	0.265
LF GBTD-Pulsed	4.4	0.2	4.2	7	31	0.08
NAV SAT	106	---	---	1	106	0.3

**estimate

*for domestic airspace coverage; based on 75×10^5 nmi^2, and effective, high accuracy circular coverage as follows:

LF GBTD-LF : 1.3×10^5 nmi^2

LF GBTD-Pulsed : 11.3×10^5 nmi^2

The overall system benefit is then:

System Type	Example	C_s
NAV SAT	NAV SAT	64
LF GBTD-Pulsed	Loran C	51
LF GBTD-CW	Decca	15
Rho-theta	PVOR/PDME	3.7
*VLF GBTD-CW	Omega	3.3
*Rho-theta	VOR/DME	1

*Do not meet the 1975-1985 area navigation/traffic control operational requirements.

7.3 SUMMARY

The ranking order of area navigation systems which comply with the 1975 to 1985 area navigation traffic control requirement and which show the most promise for implementation is:

(1) NAV SAT
(2) GBTD-pulsed
(3) GBTD-CW
(4) Rho-theta

SECTION 8

RESULTS, CONCLUSIONS AND RECOMMENDATIONS

8.1 GENERAL

The purpose of this study was to supply the NASA with insight to desirable operational characteristics of an advanced air traffic control system designed to accommodate the expected general aviation and air carrier traffic of the 1975-1985 time period.

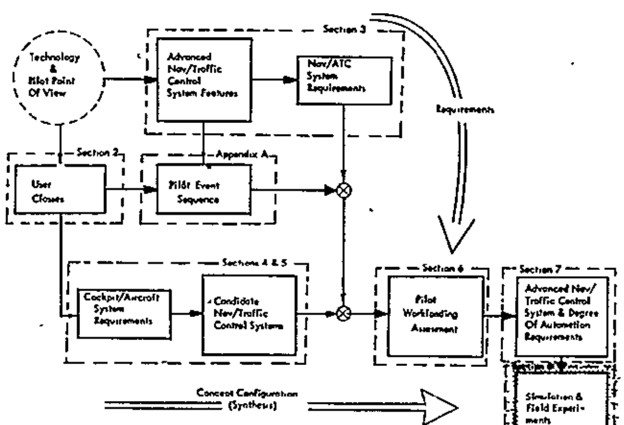

Figure 1. Block Diagram of Study Approach

In this effort the point of view of the user of the system was to be the principal criterion of acceptability. Forecast traffic densities for both the enroute and terminal airspace were used to define required system capacity. A mix of user aircraft which included three categories of general aviation aircraft and four categories of commercial carrier was assumed.

Assumptions were made about the availability and performance of five candidate navigation systems; Decca, Loran C , NAV SAT, PVOR/PDME and a hybrid radio-inertial system. For completeness, Omega was also considered.

Because none of the systems mentioned above completely satisfied the requirements set for the all-weather approach and landing phase of flight, a highly accurate, modified version of each of the Time-Difference Aids (Decca, Loran and NAV SAT) was postulated.

8.2 STUDY METHODOLOGY

A straw-man ATC system was configured around the postulated air transportation

system requirements. A basic assumption carried throughout the entire study was that all aircraft forecast to be active in the 1975-1985 time frame had to be accommodated with minimum delay, as near to the direct and optimum flight path as could be achieved, and with absolutely no compromise to safety. In addition, the system should rely as much as possible on the existing ATC structure; this is, it should be an evolutionary system.

Identification of the principal system performance requirements was determined from an analysis of user aircraft, traffic, and missions as they affected navigation, communication, and pilot information requirements. Review of air crew comments and recommendations regarding deficiencies of the existing system were combined with system capacity requirements to establish the overall desired operational characteristics and performance requirements.

In order to determine the effect on pilot workload of various system configurations, a comprehensive mission and workload evaluation model, called Event Sequence Diagrams, was developed for this study. The effect of various levels of automation and candidate navigation system technologies on pilot workload was performed.

Ground system implementation cost figures were also developed for the candidate systems, as well as an evaluation of the relative ability of the candidate systems to meet the performance criteria. The sets of information were then subjected to careful analysis, thereby permitting the nomination of a most promising candidate system along with a relative ranking of all systems considered.

8.3 RESULTS AND CONCLUSIONS

There were seven major conclusions arrived at as a result of this study:

(1) In order to accommodate the number and varieties of aircraft anticipated in the 1975-1985 time frame, all aircraft operating in controlled airspace will be required to file a flight plan. One of the major limitations in system capacity is the number of GA aircraft seeking to use the airspace.

(2) To reduce the requirements on the communications system, the pilot, and the controller, a procedure which minimizes communications and flight plan changes such as the Limit Logic concept (control-by-exception) should be adopted.

(3) In order to accommodate all the expected users of the system, the requirement to provide unambiguous navigation, position, and surveillance information allowing parallel track, all-altitude, all-area operation must be met.

(4) Automation of the communication link is required in order to accommodate all the traffic seeking to use the system. This automation will relieve the pilot and controller workload, facilitate the use of airborne generated navigation surveillance data, keep the surveillance data unambiguous, and enable the implementation of Limit Logic (control-by-exception) capability.

(5) Significant improvements in the cockpit environment can be made in both the air carrier and general aviation aircraft through a reduction in work-load. The greatest need (and also the greatest potential pay-off) will occur in the GA cockpit, where the GA pilot workload in the 1975-1985 must be reduced from its projected high level to a reasonable level in order to allow him access to controlled, congested airspace.

(6) Acceptable navigation system candidates are NAV SAT, Decca, Loran C and PVOR/PDME.

(7) The most promising candidate system for both general aviation and air carrier aircraft is the NAV SAT system.

8.3.1 Flight Plan Reference/ATC Concept.

The investigators have concluded that it will be mandatory for all users of the 1975 -1985 airspace flying in controlled airspace, whether on a VFR or IFR clearance, to be operating in accordance with an approved flight plan. The Flight Plan Reference, described fully in Section 4, is assumed to be a programmable and in-flight-retrievable insertion in both airborne navigation computer and ground-based ATC computer. The Flight Plan Reference system will require extensive computational support from the ground system in the completely automated mode.

The specific implementation of the Flight Plan Reference concept depends on user airborne systems-level of automation; and on the availability of low cost, high technology equipment.

8.3.2 Limit Logic (or control-by-exception) Concept

To reduce the need for often-repeated reports about aircraft positioning, ETA, etc., it is suggested that a procedure be used which limits all routine transmissions between aircraft and ground to a minimal output on data link of aircraft ident, way-point code and time, unless the airborne or ground based computer detects that some aspect of the aircraft's flight path or progress is not in accordance with the stored plan. The Limit Logic variables are ETA, error in altitude, and/or position relative to track, or deviations in speed or fuel remaining which are larger than some pre-assigned number.

8.3.3 Area Navigation Capability

Area navigation capability can be used to increase the capacity of the air transportation system by providing the means to operate along direct point-to-point routes; along tracks parallel to designated routes; multiple and flexible SIDs or approach paths; by permitting the designation of 3-dimensional or slant tracks; by allowing for a standardization of enroute and terminal procedures without concurrently requiring that the aircraft overfly specific ground based facilities. Used in conjunction

with the Flight Plan Reference, Limit Logic and a suitable navigation aid, the airborne system is provided the means to generate surveillance information required by the ATC system. (This in turn reduces the need for manual flight-following using Flight Strips and/or the continuous tracking of the aircraft on ground based radar.)

8.3.4 Automation of Communications

Current Practice

The workload assessment performed in this study indicates that very dramatic reductions in communication workload can be achieved for both the general aviation and air carrier pilot through use of automated data link.

For general aviation (GA1, GA2) VFR enroute flight, automation of the position information A-G function, the corresponding command uplink, and the advisory function reduces present workload normally associated with these functions by 91%; in the terminal area present workload associated with these functions is reduced by 56%.

The air carrier and general aviation (GA3) pilot operating in the enroute airspace could experience as much as a 48% reduction in workload through automation of the position report, the related command uplink function, and the advisory function. Reduction in terminal area workload could be as high as 79% through utilization of data link and automated procedures.

Advanced System

The Flight Plan Reference concept further improves the workload situation. Use of data link also ensures an unambiguous flow of surveillance information between air and ground.

8.3.5 Summary of Cockpit Workload Findings

A major undertaking of this study was the determination of the potential effect on pilot workload of various categories of automation. One of the most significant areas considered, communications, has just been described. The investigators considered ten system configurations (Appendix G) for the air carrier and GA3 users and fourteen different system configurations for GA1 and GA2 users. These latter configurations ranged from the most rudimentary systems, comprising little more than air-data-derived information plus map and pilot's DR kit, to fully automated position determination and guidance computer. Moving map displays were considered for the air carriers and GA3 only.

(I) Air Carrier and GA3 Aircraft

Air carrier and the business class of general aviation aircraft are nominally equipped with autopilots, thus aircraft pilot workload in the control and monitor tasks, while enroute, tends to be minimized. As a consequence the impact of automation on navigation and communication functions is less dramatic than it is for the GA1 and GA2 pilot. Utilization of state-of-the-art airborne general purpose computers and integrated moving map displays could reduce potential workload associated with the pilot navigation management function by as much as 86%.

Communication management workload can be reduced up to 70% depending upon the level of automation provided... simply providing automated A-G ident and acknowledgment could reduce the potential workload by 13%; adding an automated command uplink drops the level by an additional 34%; and provision of an automated format for the advisory services adds another 23%.

(2) GA1 and GA2 Aircraft

The general aviation pilot (GA2) could meet the required accuracy and surveillance requirements of the postulated 1975-1985 ATC system with any one of the following three position-determination systems: GBTD, NAV SAT, or precision rho-theta. These systems would utilize a hyperbolic coordinate converter or course line computers and air data dead reckoning computer in conjunction with an A-G data link. Pilot workload is 30 to 50% lower with this set of equipment than it would be for the GA1 system described below. The application of the ground-to-air data link could further reduce the enroute communication workload by 42%.

A minimal cost system aimed at the lower end of the GA1 dollar scale, but necessitating ground-based computation of position and steering information is conceivable. This system would allow the GA1 pilot to meet the track keeping and surveillance requirements of the 1975-85 ATC system. The system is comprised of time difference receiver incorporating automatic search, acquisition and lock to signals from either a GBTD or NAV SAT system. The communications system would consist of a minimum capacity data link on which TD information would be automatically relayed to ground followed by an uplink of distance to go and course to waypoint. Workload for such a system would be significantly high and the aircraft would be entirely dependent upon the reliability of the communications channel. Conventional VHF transceiver back-up would be employed.

The general aviation pilot (GA1, GA2) workload in controlling and monitoring aircraft flight was rated as excessive because of the absence of a low cost automatic flight control system. Decreasing the control and monitor function of the general aviation pilot would permit additional task time for navigation, hazard avoidance, and

communication functions.

8.3.6 Candidate Navigation Systems

The candidate systems which meet the operational and accuracy requirements set out in Section 5 for enroute and terminal area navigation are NAV SAT, Loran C, Decca and PVOR/PDME.

The approach and landing requirement demands accuracies which can only be met by upgraded versions of the NAV SAT and GBTD systems, called Differential Time Difference Systems.

(1) VTOL System Configuration. A radio-inertial system was configured for a large, 60-90 passenger, VTOL transport capable of meeting Cat IIb landing minima. The airborne components include an area navigation computer with vertical channel guidance; time difference receiver with a differential calibration receiver (either NAV SAT or GBTD); a radar altimeter; a marker beacon receiver; a precision distance measuring receiver; and an inertial-quality attitude reference and dead reckoning system.

8.3.7 Most Promising Candidate System.

The four successful candidate systems were compared with a standard VOR/DME position determination system integrated with course line computer. Measures of performance were calculated for each system's effectiveness in meeting the 1975-85 Navigation/ATC system capacity requirements and each candidate's total cost of implementation for the ground based equipment. These two terms were then equated. The system selected as the most promising candidate was the fully automated NAV SAT configuration.

The Loran C candidate was rated approximately 80% as effective; Decca was rated as 23% as effective on this scale; and PVOR/PDME only 6% as effective.

8.4 RECOMMENDATIONS

It is clear from a review of the major elements of this study that success in design of a safe, economic and efficient air transport system which will accommodate all air carrier and general aviation vehicles seeking to use the system will require considerable improvements in accuracy of navigation and facility of communication, reduction in cockpit workload, increased awareness and advance notice of hazards to flight, and significantly increased flexibility in the ATC system.

These improvements must be made available to all levels of GA user, thereby necessitating a family of solutions which are compatible with the minimum budget GA1 pilot. This user is characterized as having the least experience but the highest level of cockpit load. As a consequence considerable research and development is recommended in the areas set out below........solutions should be sought which are aimed in particular at GA1 and GA2 users.

Because of the potential that VTOL and STOL aircraft have to relieve congestion within the major terminal through utilization of satellite airports and landing pads, large gains in system capacity can be realized from enhancing their ability to utilize regions of the airspace not now required or contemplated for use by CTOL jets, SST and GA aircraft. In summary then, it is recommended that NASA concentrate its search for improved technologies in those areas which will result in the greatest improvement in operational capability of GA1, GA2, VTOL and STOL aircraft.

The following general areas of research would seem to offer the earliest and most significant payoffs.

(1) Increase system capacity by supporting development of a precise area navigation capability to include approach and land phase of flight capable of use by GA1 and GA2 aircraft.

(2) Improve the communication environment through development of an automated command control and surveillance link, and a non-voice advisory information system.

(3) Develop low cost hazard warning capability to include PWI, obstacle and high-ground warning, and all-weather runway detector.

(4) Develop a cockpit workload reduction program which includes simplification of information display, automated flight path manager, blunder-proof flight control and autopilot system.

(5) Develop an air transportation system evaluation tool which can be used to relate aircraft, missions, pilot and systems to an air traffic control environment. This tool should permit assessment of workload, sensitivity analyses related to system-levels of automation or variations in basic parameters affecting system capacity.

(6) Support research and development of airborne equipment which has a high probability of improving system capacity, reducing cockpit workload, minimizing hazards to flight or significantly reducing the cost of existing hardware needed by GA1 and GA2 users.

(7) Develop Operations Analysis Capability. Use to determine requirements and benefits related to ATC path stretching, speed scheduling, extend sensitivity analysis on capacity and cost benefits of candidate systems.

8.4.1 Projects Related to Increasing System Capacity

(1) Develop and evaluate the Differential Time Difference concept discussed in Section 5 for possible use with Loran C, Decca and NAV SAT.

Action Required: Perform analysis of propagation phenomena with respect to selected test sites. Develop autocorrelation functions. Specify test hardware. Perform field experiments using ground units. Perform flight test experiment to demonstrate approach and land capability.

Potential Benefit: Provide relatively low cost CAT II approach capability at large number of secondary airfields and candidate VTOL pads.

(2) Evaluate methodology which could standardize enroute and TMA area navigation procedures for use with inertial, radio-inertial and Time Difference Navigation aids.

Action Required: Study and Simulation

Potential Benefit: Standardize computer I/O requirements, cockpit procedures, communications format and coding.

(3) Simulate and evaluate Flight Plan Reference and Limit Logic Methodologies discussed in section 4.

Action Required: Develop algorithm which permits simulation and evaluation of these methodologies.

Potential Benefit: Establish requirements on airborne and ground based computers, I/O requirements and verify feasibility of concept.

8.4.2 Improve the Communications Environment

(1) Develop and Evaluate an automated control and surveillance data airborne communications link. This system will be required to off-load pilot workload, to support the surveillance information output from the aircraft, to support the Flight Plan Reference concept, to supply the secure path for Limit Logic transmissions, and problems related to defining, relaying and monitoring great circle tracks.

Action Required: Establish Data Link performance requirements; develop algorithm to simulate ATC and navigation system inputs. Evaluate in simulator.

Potential Benefit: Reduction in cockpit workload; increase potential for GA aircraft to comply with ATC system; stimulate development of Flight Plan Reference and Limit Logic Concepts. Establish performance requirements on future data link system.

(2) Non-voice Advisory Information System. Investigate the desirability of supplying meteorological, airport and runway situation, NOTAMS, expected traffic and similar routine data through use of TV channel and suitable cockpit display.

Action Required: Study and simulation

Potential Benefit: Reduction in workload, improved information transfer to pilots of marginal proficiency, reduction of chatter on radio.

8.4.3. Develop Low Cost Hazard Warning Equipment.

A requirement exists to provide GA aircraft with a gross warning about potential hazards from nearby aircraft, cloud, precipitation and turbulence; high ground and man-made obstacles to flight; and the location of the runway regardless of runway composition. Develop rules for use in remote sensor detection of other aircraft vis-a-vis ship to ship avoidance problems.

Action Required: Investigate the feasibility of employing low-cost modifications to existing weather radars to provide required capability. Consider transponders for PWI role, interferometric auxiliary antennas for high ground detection, and cheap dipoles for runway centerline illumination.

Potential Benefits: Major reduction in current accident rate.

8.4.4 Cockpit Workload Reduction Program.

Major effort is required in the development of simplified cockpit instrumentation, improved navigation and fuel management capability, and improved low-cost autopilot systems.

(1) Simplification of Information Display. There is a need to reduce the number and complexity of instruments presently required to fly under all conditions of weather. Displays are required which present "action required" information. For example, the pilot infers the presence of a system malfunction from what is often second or third order information. Thereafter, he must recall from training the necessary corrective action. He should be told that a particular malfunction exists and precisely what corrective action to take.

Action Required: Human factors research effort related to cockpit decision theory.

(2) Automated Flight Path Manager. The future ATC system will make extensive use of 3-D slant tracks and ETA control through speed scheduling and/or path stretching. Pilots will need a special purpose computer and display to aid them in determining course, distance speed and fuel-related problems.

(3) Autopilot Modes. A requirement exists in many aircraft to provide the pilot with added safeguards against blunder and excessive workload.

Action Required: Develop low cost improved flight control and autopilot systems for GA. Include a mode of operation which is capable of preventing stall, upset...or if either has occurred, will right the aircraft.

Potential Benefit: Reduction of workload and accident rate.

(4) Cockpit Mockup – Development of a cockpit mockup to be used in verifying and validating NAVTRACS procedures, event sequence diagrams, avionics system utilization, and pilot workload estimates, is a very desirable study adjunct. This mockup and associated analysis charts and time line diagrams should then be used to determine task times for NAV SAT, GBTD and precision rho-theta systems configured in general aviation systems g7 . . . g14. Mockup evaluation should then be conducted for air carrier systems v1 . . . v10. Exercise the advanced system procedures and operations to validate workload, system capacity, and refine the system operation.

(5) Dynamic General Aviation Simulation – Extend the cockpit mockup tests to a GAT-1 simulator to validate the general aviation pilot's use of systems g7 . . . g14. Evaluate pilot control and monitor workload, navigation management workload, and communications management workload in the dynamic but controlled environment. Devise controls on the experiment to assess variations in pilot workload to cope with winds, turbulence, and contingency communications (Appendix A). Determine the general aviation pilot's ability to cope with the advanced navigation/traffic control environment with advanced avionics systems, in a controlled but dynamic test vehicle. Initially, interface the system to a single ground surveillance and control team. Then expand tests to incorporate ATC traffic control environment with 1975-1985 traffic densities and STOL, VTOL, CTOL, and SST aircraft.

8.4.5 Develop an ATS Evaluation Tool

A major development of the NAVTRACS study was the generation of an event-oriented model of an advanced navigation ATC system. This model was a fundamental tool in the determination of navigation and communication management tasks and the resulting workload conclusions. It is strongly recommended that this model be developed into a large scale event-oriented navigation/traffic control system siumlation.

Action Required: Develop required software and implement model on ERC computer. Subroutines will be required for each user vehicle, system component, flight path control procedure. Simulate Flight Plan Reference and Limit Logic.

Potential Benefits: Provide the means to perform tradeoff analyses between candidate navigation and ATC systems. A second objective of this program is to verify the conclusions of the NAVTRACS program through brief simulation, and to develop a system tradeoff tool for the mission analyst, system designer and systems analyst for use in evaluating pilot, navigation systems, traffic control, aircraft and avionic system parameters based on the NAVTRACS Program Methodology. The methodology would be programmed to permit:

(1) verification of NAVTRAC's concepts

(2) determination of advanced technology program objectives from air traffic control missions

(3) quantification of air traffic control concepts such as the recommended flight plan reference or other system concepts--allowing

(a) decreased workloading

(b) increased capacity in terms of navigation aids

(c) increased safety

(4) time-line analysis

(5) % utilization of pilot

(6) route analysis

(7) safety studies

(8) sensitivity studies for revision of navigation/traffic control systems

(9) cost benefit, effectiveness analysis

(10) definition of air and ground system characteristics for the purpose of defining advanced technology programs, for example

(a) system needs

(b) synthesis of system options, sensitivity to the option

(c) data processing automation requirements

(d) software and equipment requirements

Figure 83 shows the simulation program flow chart. Inputs to the program include: the area navigation/traffic control event sequence diagrams (contained in Appendix A); the traffic control route structure; the number of aircraft, and their specific type and performance parameters; the avionics subsystems; performance parameters and the pilot communication, control and monitor, and navigation management tasks (examples shown in Apendices D, G, H); and the subsystem and navaid performance parameters.

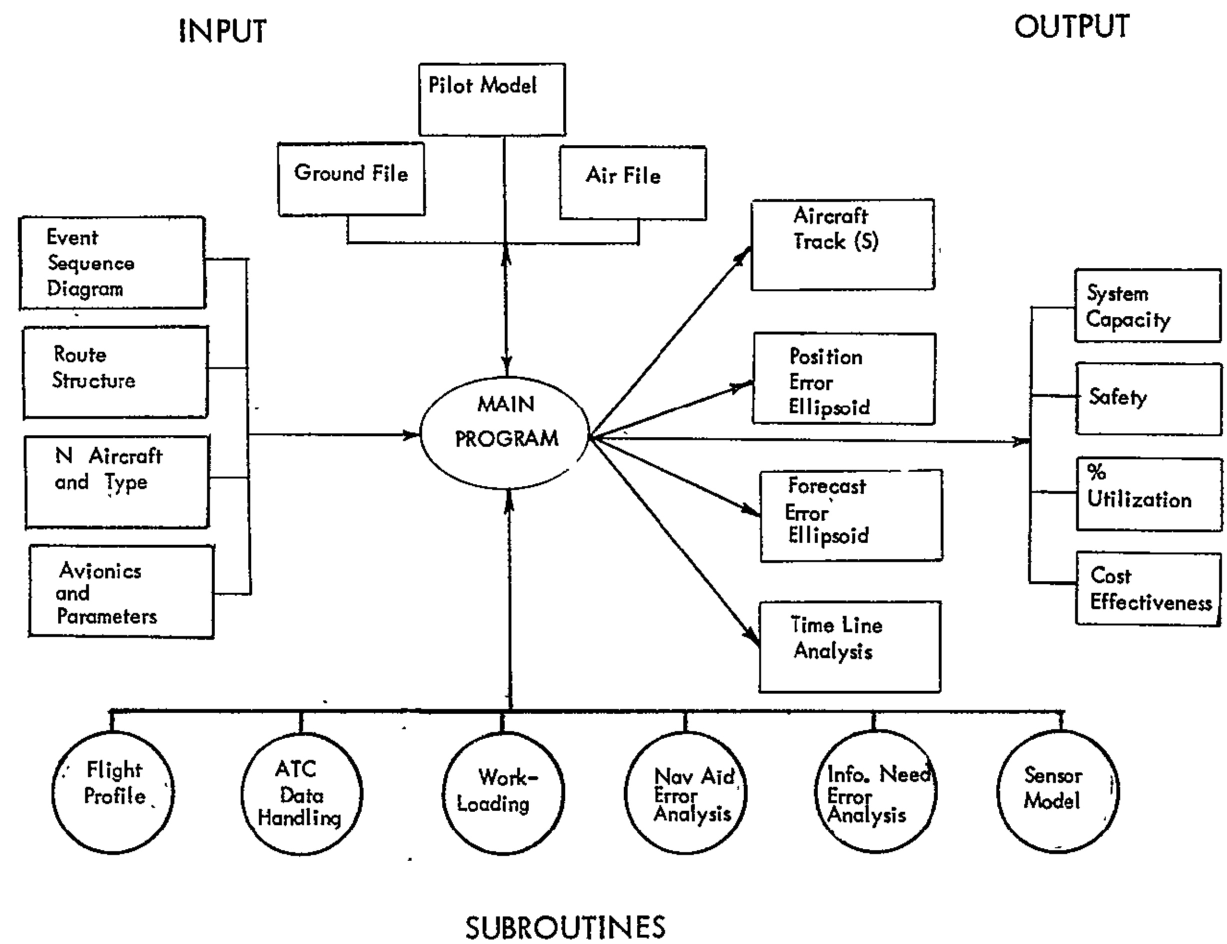

Figure 83 Digital Simulation of NAVTRACS Methodology

8.4.6 Support R & D of New Technologies

The workload evaluation performed in NAVTRACS indicates the desirability of sponsoring development work on a number of equipments both for general aviation and the air carriers.

(1) Low cost special-purpose computer and receiver for use with either GBTD or NAVSAT. Its function would be to dead reckon, supply signal acquisition information to assist in lock-on, and to perform the coordinate conversion. The computer would also act as a store for the Flight Plan Reference, would contain specified limit logic, and would interface with the data link.

(2) Develop a minimum capacity data link for use with the advanced NAV/ATC system.

(3) Develop a simplified cartographic scheme for presentation of navigation on moving map displays.

(4) Perform a thorough Cost/Benefit evaluation of Head-up and Head-down Displays. Develop a universal software package which will allow for variations in information content and format.

(5) Develop an along track/cross track computer-receiver for use with the early single-satellite programs. Objective will be to derive a cross-track signal of sufficient accuracy to meet the 1972-75 North Atlantic lateral separation criteria.

8.4.7 Develop Operations Analyses Capability

Actions Required:

(1) Evaluate ATC-related control time maneuvers for their compact or airborne computers, control-display, and communications requirements.

(2) Extend sensitivity analysis developed in section 7 to account for variations in, or increase in number of, input variables.

(3) Develop a flight planning algorithm which will permit the integration of meteorological data, traffic forecasts and measurements, aircraft performance, user route requirements, topographic and other special limiting factors, so that a technique for Best Flight Path selection is derived.

Potential Benefits: Automated clearances should facilitate flow of traffic, thus increasing system capacity and reducing workload.

REFERENCES

1. "Independent Surveillance and Communication Using Satellites," N68-24501, August 1967.

2. "Preliminary Report on the SOA of Omega," N67-10030, August 1966.

3. "Second Report on Omega, Differential Omega and OPLE," N68-23973, April 1968.

4. "Transmission of Characteristic Data and Range Measurement in ATC," N67-18445, 1965.

5. "Alternative Approaches for Reducing Delays in Terminal Areas," N68-12177, November 1967.

6. "The Current State of the SUD-LEAR Programme to Reduce Landing Minima and Develop an All-Weather Landing System," N68-11611, 1965.

7. "Study on the Feasibility of V/STOL Concepts for Short-Haul Transport Aircraft," NASA CR-670, January 1967.

8. "Feasibility on V/STOL Concepts for Short-Haul Transport Aircraft," NASA CR-743, May 1967.

9. "Supplement to Feasibility on V/STOL Concepts for Short-Haul Transport Aircraft," NASA CR-743(1), September 1968.

10. "Empirical Human-Factors Investigation of Display Design," N67-29922, April 1967.

11. "Jets in a Horse and Buggy Era," N67-22270, December 1966.

12. "Meeting the Problems of Success," N67-22268, December 1966.

13. "Airborne Radar for Helicopter Navigation," N67-27193, September 1966.

14. "Dallas/Ft. Worth Regional Airport Simulation Study," N67-27188, April 1967.

15. "Technical and Economic Evaluation of Aircraft for Intercity Short-Haul Transportation," Vol. I, N67-10599, April 1966.

16. "Technical and Economic Evaluation of Aircraft for Intercity Short-Haul Transportation," Vol. II, N67-10595, April 1966.

17. "Technical and Economic Evaluation of Aircraft for Intercity Short-Haul Transportation," Vol. III, N67-12024, April 1966.

18. "Study of the Optimum Values of Several Parameters Affecting Longitudinal Handling Qualities of VTOL Aircraft," NASA TN D-4624, July 1968.

19. "Aviation and the Transportation System," N67-22267, February 1967.

20. "Final Report: Field Appraisal of the Advanced Radar Traffic Control System, [ARTS]," N68-13946, October 1967.

21. "Field Appraisal of the Advanced Radar Traffic Control System - Appendix," N68-13945, October 1967.

22. "OPLE Experiment," N67-36634, June 1967.

23. "Weather Conditions Affecting VTOL Operations in the Northeast Corridor," N68-11922, November 1966.

24. "Crab Angle Sensing System," N68-15233, November 1967.

25. "Technological Gaps in V/STOL Development," N68-12964, October 1967.

26. "Factors Influencing the Choice of Facilities and Techniques for Aeronautical Development," N68-25578, April 6, 1967.

27. "Simulation Technology," N68-22824, April 1967.

28. "Proposed Analytical Model for the Final Stages of Landing a Transport Airplane," NASA TN D-4438, June 1968.

29. "Summary of VGH Data . . . . . Airline Operations," NASA TN D-4529, May 1968.

30. "Trends in Repeated Loads on Transport Airplanes," NASA TN D-4586, May 1968.

31. "Simulation Studies of the SST in the Present-Day ATC System," NASA TN D-4638, July 1968.

32. "A Simulator Study of a Pictorial Navigation Display in Instrument Departure of the SST," NASA TN D-4029, July 1967.

33. "ATC Concepts for Supersonic Vehicles - Part I," N67-13246, August 1966.

34. "ATC Concepts for Supersonic Vehicles - Part II-1," N67-38953, August 1967.

35. "ATC Concepts for Supersonic Vehicles - Part II-2," N68-13158, November 1967.

36. "An Experimental Investigation of Compensatory and Pursuit Tracking Displays with Rate and Acceleration Control Dynamics and a Disturbance Input," NASA CR-1082, June 1968.

37. "Some Studies Into Improvements in Automatic Throttle Control," N68-13060, September 1967.

38. "The Pilot's Safety Problem in CAT II Operations and the Potential Contribution of HUD," N68-12865, June 1966.

39. "The Effect of Low Altitude Gusts on Automatic Landing," N68-25286, September 1966.

40. "Avionics Requirements for All-Weather Landing of Advanced SST's," N67-28753, April 1967.

41. "All-Weather Landing Simulation for CAT III, Airborne Configuration," Vol. I, N68-12238, July 1967.

42. "All-Weather Landing Simulation for CAT III Airborne Configuration," Vol. II, N67-39703, July 1967.

43. "New York Interim Common Tracon Facility Simulation Study," N67-10448, October 1967.

44. "Evaluation of a High-Gain VHF/UHF Communication Facility," N67-39295, July 1967.

45. "Human Factors Evaluation of a Large Screen Radar Display," N67-27189, March 1967.

46. "Cockpit Instrumentation and Layout," IATA, May 1960.

47. "Analysis of Control-Display Limitations in Multi-Jet Transport Aircraft," GGC/EE/64-4, June 1964.

48. "The Allotment of Probability Shares," Memo PE-18, April 1966.

49. "Navigation Management Operational Study-Civil Air Transport Application," Polhemus Associates, Lear Seigler Inc., October 1966.

50. Journal of the Institute of Navigation, Vol. 15, No. 2, Summer 1968.

51. "The Requirement for Height Measurement in the SST," ION-British, January 196

52. "Study of a Navigation and Traffic Control Technique Employing Satellites," TRW 08710-6015-R000, December 1967.

53. Glen M. Harold, "Trends in Computer Technology," presented at the 24th Annual Meeting, Institue of Navigation, Monterey, California, June 19-21, 1968.

54. "Recent Advances in Display Media," NASA SP-159, 1968.

55. "Peripheral Vision Displays," NASA CR-808, June 1967.

56. "Take-Off Tests on a Transport Aircraft Including the Use of a 'SCAT' Take-Off Director," N68-24790, 1968.

57. "Aviation Demand and Airport Facility Requirement Forecasts for Large Air Transportation Hubs through 1980," N68-10267, August 1967.

58. "A Digital System for Position Determination," reprint from IRE Transaction of the PG SET, Vol. SET-5, No. 1, March 1959.

59. "Automatic Landing - Recent R.A.E. Contributions," N67-29925, October 1967.

60. "SST ATC Simulation Trials," TEU/S2;028, August 1967.

61. "Comparison of Information Display Concepts for Landing of VTOL Aircraft," NASA TN D-4861, November 1968.

62. "A Simulator Investigation of the Problems of Visual Taxi Guidance in Low Visibilities," N68-21987, August 1967.

63. "KLM-Research on the Lowering of Weather Minima for Landing of Aircraft," N68-12794, August 1967.

64. "Preliminary Quantitative Analysis of Airborne Weather Radar," N68-15598, December 1967.

65. "Cost/Benefit Analysis for All-Weather Landing System (AWLS) - CAT II and III," N68-12879, October 1967.

66. "Enroute IFR Air Traffic Relationships," N68-14021, November 1967.

67. "Tactical V/STOL Weapon System Control Display Requirements Study for the Navigator's Station," PAI-TR-66-2, July 1966.

68. "SOA for V/STOL Control Display," RTD-TDR-63-4167, October 1963.

69. "Preliminary V/STOL Control-Display Subsystem Requirements Study," FDL-TDR-64-85, June 1964.

70. "Navigation/Traffic Control Satellite Mission Study," Technical Proposal Document P-67061, June 8, 1967.

71. "Third Annual NASA-University Conference on Manual Control," NASA SP-144, USC, Los Angeles, California, March 1-3, 1967.

72. Survey Officer's Manual, "The Application of LORAC to Precision Terrestial Line-Length Measurement and Position Fixing," AD 232 017 (no date)

73. "Satellite Navigation Studies Progress Report - 10/1/65 - 9/30/66," Contract No. NASr-54(10), May 1967.

74. "Phase Difference Navigation Satellite Study," N67-34257, June 1967.

75. "A Descriptive Model for Determining Optimal Human Performance in Systems," Vol. III, CR-878, March 1968.

76. D. T. McRuer and E. S. Krendel, "Dynamic Response of Human Operators," USAF WADC TR 56-524, 1957.

77. "Extract of the Study about Potential Roles of SST Crews and Some Implications of the Flight Deck," NASA CR-561, undated.

78. Sheldon Razin, "Explicit (Noniterative) Loran Solution," Navigation, Fall 1967, Vol. 14, No. 3.

79. "Application of the Airborne General Purpose Digital Computer in Air Data Systems," Appendix A - Computer Survey, Polhemus Associates, Inc., 1967.

80. World Distribution and Characteristics of Atmospheric Radio Noise, Report No. 322, Documents of the Xth Plenary Assembly of the International Radio Consultativ Committee at Geneva, 1963, International Telecommunication Union, Geneva, 196

81. A. D. Watt and R. W. Plush, "Power Requirements and Choice of an Optimum Frequency for a Worldwide Standard-Frequency Broadcasting Station," Journal of Research, National Bureau of Standards, Vol. 63D, No. 1, July-August 1959, pp. 35-44.

82. E. R. Swanson, "VLF Radio Navigation Systems," Modern Navigational Systems - Fundamentals and Applications, University of Michigan Engineering Summer Conference, Ann Arbor, July 22-August 2, 1968.

83. J. A. Pierce, "Intercontinental Frequency Comparison by Low-Frequency Radio Transmission," Proc. IRE, Vol. 45, No. 6, June 1957, pp. 794-803.

84. W. L. Taylor, "VLF Attenuation for East-West and West-East Daytime Propagation Using Atmospherics," Journal of Geophysical Research, Vol 65, No. 7, July 1960, pp. 1933-1938.

85. J. E. Howell, "Geodetic Secor," presented at the XIV Symposium of the Avionics Panel of the Advisory Group for Aerospace Research and Development (AGARD-NATO) on Advanced Navigational Techniques, Milan, Italy, September 12-15, 1967.

86. J. R. Johler, W. J. Kellar and L. C. Walters, Phase of the Low Radio-frequency Ground Wave, National Bureau of Standards Circular 573, U. S. Department of Commerce, Washington, D. C., June 26, 1956.

87. C. Williams, "Low Frequency Radio Wave Propagation by the Ionosphere with Particular Reference to Long-Distance Navigation," Proc. I.E.E., 98, Part III, March 1951, pp. 81-103.

88. R. E. Scott, "Low Frequency Propagation," Modern Navigational Systems - Fundamentals and Applications, University of Michigan Engineering Summer Conference, Ann Arbor, July 22-August 2, 1968, Chapter 15.

89. J. R. Johler and L. A. Berry, Loran-D Phase Corrections Over Inhomogeneous, Irregular Terrain, ESSA Technical Report IER 59 - ITSA 56, Institute for Telecommunication Sciences and Aeronomy, Boulder, Colorado, November 1967.

90. James R. Wait, "Amplitude and Phase of the Low-Frequency Ground-Wave Near a Coastline," Journal of Research, National Bureau of Standards, Vol 58, No. 5, May 1957.

91. J. O'Day, "Errors in the Field of a Low Frequency Hyperbolic Navigation System in Mountainous Terrain," Modern Navigational Systems - Fundamentals and Applications, University of Michigan Engineering Summer Conference, Ann Arbor, July 22-August 2, 1968, Chapter 26.

92. R. A. Volz, "Application of Correlation and Measurement Techniques to the Calibration of Errors in Low-Frequency Navigation Systems," Modern Navigational Systems - Fundamentals and Applications, University of Michigan Engineering Summer Conference, Ann Arbor, July 22-August 2, 1968, Chapter 25.

93. Final Report of the Ad Hoc Joint Navigation Satellite Committee, May 1966.